



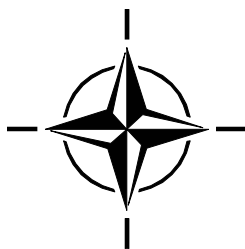
RTO TECHNICAL REPORT

TR-HFM-078

Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

(Véhicules militaires sans pilote (UMV) :
Questions relatives aux facteurs humains
liés à l'augmentation des forces)

Final Report of the RTO Human Factors and Medicine
Panel (HFM) Task Group HFM-078/TG-017.



Published July 2007





RTO TECHNICAL REPORT

TR-HFM-078

Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

(Véhicules militaires sans pilote (UMV) :
Questions relatives aux facteurs humains
liés à l'augmentation des forces)

Final Report of the RTO Human Factors and Medicine
Panel (HFM) Task Group HFM-078/TG-017.

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

The content of this publication has been reproduced
directly from material supplied by RTO or the authors.

Published July 2007

Copyright © RTO/NATO 2007
All Rights Reserved

ISBN 978-92-837-0060-9

Single copies of this publication or of a part of it may be made for individual use only. The approval of the RTA Information Management Systems Branch is required for more than one copy to be made or an extract included in another publication. Requests to do so should be sent to the address on the back cover.

Table of Contents

	Page
List of Figures	xv
List of Tables	xix
Contributing Authors	xxi
 Executive Summary and Synthèse	 ES-1
 Chapter 1 – Introduction	 1-1
1.1 The Issues	1-1
1.2 Scenarios and Military Relevance	1-2
1.3 Theoretical Frameworks	1-3
1.4 System of Systems	1-4
1.5 Artificial Cognition and Cooperative Automation	1-5
1.6 Controls and Displays	1-6
1.7 Human-Automation Integration	1-7
1.7.1 Problems with Supervisory Control Tasks	1-8
1.7.2 Function Allocation	1-8
1.7.3 Levels of Automation	1-8
1.7.4 Multi-Agent Adjustable Autonomy	1-8
1.7.5 Levels of Automation within the Air Vehicle	1-9
1.8 Putting It All Together	1-9
 Chapter 2 – Military Relevance	 2-1
2.1 Part I – Military Relevance of Human Factors of UMV Systems	2-1
2.1.1 Introduction	2-1
2.1.1.1 References	2-1
2.1.2 Human Factors	2-2
2.1.2.1 User Requirements	2-2
2.1.2.2 Integration of Human and Automation Requirements	2-4
2.1.2.3 References	2-7
2.1.3 Operational Benefits of UMVs	2-8
2.1.3.1 Uninhabited Ground Vehicles	2-8
2.1.3.2 Uninhabited Underwater Vehicles	2-11
2.1.3.3 Uninhabited Air Vehicles	2-13
2.1.3.4 Summary of UMV Missions, Roles and Tasks	2-20
2.1.3.5 References	2-22
2.1.4 Command and Control	2-23
2.1.4.1 NATO Air Command and Control System	2-24
2.1.4.2 Interoperability	2-25
2.1.4.3 References	2-25

2.1.5	Legal and Moral Issues	2-26
2.1.5.1	Legal Issues	2-26
2.1.5.2	Discrimination	2-27
2.1.5.3	Humanity	2-28
2.1.5.4	Accountability	2-28
2.1.5.5	Legal Implications	2-29
2.1.5.6	Moral and Ethical Issues	2-29
2.1.5.7	References	2-31
2.1.6	UMV Use Cases	2-31
2.1.6.1	UAV Use Case	2-32
2.1.6.2	Integration of UAV and Manned Aircraft Systems	2-34
2.1.6.3	UUV and UGV Use Cases	2-37
2.1.6.4	Composite UMV Use Case	2-38
2.1.6.5	References	2-41
2.1.7	Acknowledgements	2-42
2.2	Part II – Military Relevance for Uninhabited Aerial Vehicles (UAVs)	2-42
2.2.1	Introduction	2-42
2.2.2	The Map of Relevance	2-43
2.2.3	The Human Axiom	2-43
2.2.3.1	The Philosophy	2-44
2.2.3.2	The Automation Paradox	2-45
2.2.3.3	The Human Paradox	2-45
2.2.3.4	The Principle of Uncertainty	2-46
2.2.3.5	The Principle of Control	2-47
2.2.3.6	Designed and Applied Effect, Robustness, Versatility and Flexibility	2-48
2.2.3.7	The Principle of Necessity – The Human Axiom	2-48
2.2.4	Platform Characteristics	2-48
2.2.5	Interaction (Control) Characteristics	2-49
2.2.6	Relative Strengths	2-50
2.2.7	Relative Weaknesses	2-50
2.2.8	Summary and Relevance	2-51
Chapter 3 – Theoretical Frameworks		3-1
3.1	Introduction	3-1
3.1.1	Background	3-1
3.1.1.1	Reducing Operator to Vehicle Ratio	3-1
3.1.1.2	Interoperability	3-3
3.1.1.3	Research and Development Areas	3-3
3.1.2	Why Theoretical Frameworks	3-4
3.1.3	Scope of Theoretical Frameworks Theme	3-5
3.1.3.1	Human Performance Models	3-5
3.1.3.2	Humans as Part of a System Models	3-5
3.1.3.3	Human Cognition Models	3-5
3.1.4	Identifying Relevant Theoretical Frameworks	3-5
3.2	Framework Descriptions	3-7
3.2.1	Literature Review	3-7

3.2.1.1	Models for the Design of Human Interaction with Complex Dynamic Systems	3-7
3.2.1.2	A Theoretical Analysis and Preliminary Investigation of Dynamically Adaptive Interfaces	3-8
3.2.1.3	Integrating Perceptual and Cognitive Modeling for Adaptive and Intelligent Human-Computer Interaction	3-8
3.2.1.4	Adaptive Interfaces for Human-Computer Interaction: A Colourful Spectrum of Present and Future Options	3-9
3.2.1.5	The Future of Watchstation Design: Evolution from Single Purpose to Intelligent Watchstations	3-9
3.2.1.6	An Architecture for Intelligent Interfaces: Outline of an Approach to Supporting Operators of Complex Systems	3-10
3.2.1.7	A Model for Types and Levels of Human Interaction with Automation	3-10
3.2.2	Frameworks from Survey Returns	3-11
3.2.2.1	Cognitive Automation (CA)	3-11
3.2.2.2	Extended Control Model (ECOM)	3-11
3.2.2.3	Multiple Agent Interaction (MAI) Model	3-12
3.2.2.4	Military Relevance Philosophy (MRP)	3-12
3.2.2.5	Playbook (PB)	3-13
3.2.2.6	System Process/Task Organisational Model for HF V&V (SPTO)	3-14
3.3	Survey Results	3-15
3.4	Discussion	3-17
3.4.1	Operator to UMV Ratio	3-17
3.4.2	Interoperability	3-17
3.4.3	Applications and UMV Situations	3-17
3.4.4	Common and Unique Framework Elements	3-18
3.5	Summary	3-19
3.5.1	Recommendations	3-19
3.6	Chapter 3 References	3-19
Appendix 3-1: Phase I – Literature Review		3-22
A3-1.1	Literature Search and Preliminary Review	3-22
A3-1.2	Papers Reviewed in Detail	3-23
A3-1.2.1	Special Issue on Intelligent Interface Technology: Editor's Introduction	3-23
A3-1.2.2	Steps to Take before Intelligent User Interfaces Become Real	3-24
A3-1.2.3	Models for the Design of Human Interaction with Complex Dynamic Systems	3-25
A3-1.2.4	A Theoretical Analysis and Preliminary Investigation of Dynamically Adaptive Interfaces	3-25
A3-1.2.5	Integrating Perceptual and Cognitive Modeling for Adaptive and Intelligent Human-Computer Interaction	3-26
A3-1.2.6	Adaptive Interfaces for Human-Computer Interaction: A Colourful Spectrum of Present and Future Options	3-26
A3-1.2.7	Intelligent User Interfaces: An Introduction	3-27
A3-1.2.8	The Future of Watchstation Design: Evolution from Single Purpose to Intelligent Watchstations	3-27
A3-1.2.9	An Architecture for Intelligent Interfaces: Outline of an Approach to Supporting Operators of Complex Systems	3-28
A3-1.2.10	A Model for Types and Levels of Human Interaction with Automation	3-28

A3-1.3	Comments on the Literature Reviewed in Detail	3-29
A3-1.3.1	What Does Interaction Model Do?	3-29
A3-1.3.2	What Key Functions should an Interface Have?	3-30
A3-1.3.3	What Interaction Level should an Interface Have?	3-31
Appendix 3-2: Comments on Theoretical Framework for Uninhabited Military Vehicles by E. Hollnagel		3-33
A3-2.1	Force Multiplication	3-33
A3-2.2	UMV Scenarios / Use-Cases	3-34
A3-2.3	Theory Evaluation	3-34
A3-2.4	References	3-34
Appendix 3-3: Request for Comments on Theoretical Frameworks for Uninhabited Military Vehicles by C. Miller		3-35
A3-3.1	Force Multiplication	3-36
A3-3.2	UMV Scenarios / Use-Cases	3-36
A3-3.3	Theory Evaluation	3-37
A3-3.4	References	3-37
Appendix 3-4: Request for Comments on Theoretical Frameworks for Uninhabited Military Vehicles by P. Stensson		3-39
A3-4.1	Force Multiplication	3-39
A3-4.2	UMV Scenarios / Use-Cases	3-39
A3-4.3	Theory Evaluation	3-39
Appendix 3-5: Request for Comments on Theoretical Frameworks for Uninhabited Military Vehicles by P. Farrell		3-40
A3-5.1	Design Implications for Multiple Agent Systems	3-40
A3-5.2	Force Multiplication	3-41
A3-5.3	UMV Scenarios / Use-Cases	3-42
A3-5.4	Theory Evaluation	3-42
A3-5.5	References	3-43
Appendix 3-6: Request for Comments on Theoretical Frameworks for Uninhabited Military Vehicles by A. Schulte		3-44
A3-6.1	Force Multiplication	3-44
A3-6.2	UMV Scenarios / Use-Cases	3-44
A3-6.3	Theory Evaluation	3-45
Appendix 3-7: Request for Comments on Theoretical Frameworks for Uninhabited Military Vehicles by I.S. MacLeod		3-46
A3-7.1	Introduction	3-46
A3-7.2	The System Process / Task Organisational Model for HF V&V	3-47
A3-7.3	Question / Response	3-47
A3-7.4	Augmenting Reality	3-49
A3-7.5	References	3-49

Chapter 4 – System of Systems

4-1

4.1	Introduction	4-1
4.2	Command and Control: Human Information Processing and Trust in Time Delayed Systems	4-2
4.2.1	Human Information Processing (HIP) Capabilities, Limitations, and Detractors	4-2
4.2.1.1	Human Information Processing Models	4-2
4.2.1.2	Environmental Stressors that Degrade Cognitive Performance	4-3
4.2.1.3	The Need to Support Supervisory Control to Enhance Information Management	4-6
4.2.1.4	References	4-6
4.2.2	User-Centric Information Management Concepts for Autonomous UUV Command and Control	4-8
4.2.2.1	Multi-Modal Interfaces	4-9
4.2.2.2	Three Dimensional Visualization	4-11
4.2.2.3	Data Fusion	4-11
4.2.2.4	Decision Aiding	4-12
4.2.2.5	References	4-13
4.2.3	Trust in Time Delayed Systems	4-15
4.2.3.1	UUV and Time Delays	4-15
4.2.3.2	Move and Wait, a Strategy Facing Time Delays	4-16
4.2.3.3	Visual Perception and Time Delays	4-17
4.2.3.4	References	4-18
4.2.4	Uninhabited Military Vehicles and Trust	4-19
4.2.4.1	Time Delays and Representations	4-19
4.2.4.2	Representation and Understanding	4-19
4.2.4.3	Understanding and Trust	4-19
4.2.4.4	Conclusions	4-21
4.2.4.5	References	4-21
4.2.5	Future Research	4-23
4.2.5.1	Multi-Modal Interfaces	4-24
4.2.5.2	Augmented Cognition	4-24
4.2.5.3	Chat Applications	4-25
4.2.5.4	Decision Aiding for Autonomous UUV Swarm Control	4-25
4.2.5.5	References	4-26
4.3	Migration of Operator Control: Human Factors and Teaming Issues	4-27
4.3.1	Background	4-27
4.3.1.1	References	4-27
4.3.2	Migration of UAV Operator Control	4-28
4.3.2.1	Levels of Control	4-28
4.3.2.2	Types of Control Migration	4-29
4.3.2.3	References	4-30
4.3.3	Reasons for Migrating Operator Control	4-30
4.3.3.1	Limitations Necessitating Control Migration	4-30
4.3.3.2	Advantages of Control Migration	4-32
4.3.3.3	Disadvantages of Migrating Operator Control	4-35
4.3.3.4	References	4-36
4.3.4	Effects of Control Migration on Concept of Teams	4-40
4.3.4.1	Teams versus Groups	4-40

4.3.4.2	Types of Teams	4-40
4.3.4.3	Distributed and Dynamically Changing Teams	4-41
4.3.4.4	Dimensions of Team Performance	4-42
4.3.4.5	References	4-44
4.3.5	Important Issues in Control Migration	4-45
4.3.5.1	Interoperability	4-45
4.3.5.2	Procedures for Migration of Control	4-45
4.3.5.3	Team Situational Awareness	4-46
4.3.5.4	Priorities in Sharing Information	4-47
4.3.5.5	References	4-47
4.3.6	Future Challenges	4-48
4.3.6.1	References	4-50
4.4	Manpower and Skills	4-51
4.4.1	Selecting UMV Crews	4-51
4.4.1.1	Introduction and an Alternative Crew Selection Method	4-51
4.4.1.2	Experimental Design	4-52
4.4.1.3	Results and Discussion	4-53
4.4.1.4	Concluding Remarks	4-54
4.4.1.5	References	4-55
4.5	Uninhabited Military Vehicle Operator Training	4-55
4.5.1	Training of Decision Making Skills Based on Critical Thinking	4-55
4.5.1.1	References	4-58
4.5.2	Embedded Training for UMV Crews	4-59
4.5.2.1	Introduction	4-59
4.5.2.2	What is Embedded Training?	4-61
4.5.2.3	Why Combine Real and Simulated Systems?	4-61
4.5.2.4	The Architectural Concept of Embedded Training	4-62
4.5.2.5	Safeguarding for Embedded Training	4-64
4.5.2.6	Choosing an Embedded Training Architecture	4-65
4.5.2.7	Team Training to be Addressed with Embedded Training	4-65
4.5.2.8	Conclusions	4-67
4.5.2.9	References	4-67

Chapter 5 – Artificial Cognition and Co-operative Automation **5-1**

5.1	Scope	5-2
5.1.1	Typical Scenario from the Military Aviation Domain	5-2
5.1.2	Forces Structure	5-3
5.1.3	References	5-4
5.2	The Work Process and Conventional Automation's Solution	5-4
5.2.1	The Work System	5-4
5.2.2	The Hierarchy of a Conventional Guidance and Control System	5-7
5.2.3	References	5-10
5.3	Problem Definition	5-11
5.3.1	Shortfalls with Conventional Automation	5-11
5.3.2	Perspectives of Future Automation	5-13
5.3.2.1	Cognitive Automation	5-14
5.3.2.2	Automatic and Autonomous Performance	5-15

5.3.2.3	Cognitive Automation as Part of the Operation-Assisting Means	5-17
5.3.2.4	Co-operative Automation as By-Product of Cognitive Automation	5-18
5.3.3	Technological Challenges	5-19
5.3.4	References	5-21
5.4	Approaching Cognition	5-22
5.4.1	Model of Human Performance	5-23
5.4.2	Modelling Approaches for Intelligent Machine Behaviour	5-25
5.4.3	The Cognitive Process as Approach to Cognitive Automation	5-29
5.4.4	References	5-32
5.5	Cognitive Systems Architecture – Realisation Aspects	5-33
5.5.1	References	5-35
5.6	Applied System Approaches	5-35
5.6.1	Artificial Intelligence (AI) Methods Perspective	5-36
5.6.1.1	Introduction to AI Methods	5-36
5.6.1.2	UAV/UCAV Autonomy Requirements	5-37
5.6.1.3	Applicability of AI Techniques to Mission Requirements	5-38
5.6.1.4	Recommended Applications of AI Methods	5-41
5.6.1.5	Conclusions on AI Methods	5-42
5.6.1.6	Recommendations on AI Methods	5-43
5.6.1.7	References	5-44
5.6.2	Intelligent, Adaptive Help System Design	5-44
5.6.2.1	The CommonKADS Methodology	5-45
5.6.2.2	Application of CommonKADS to Help System Design	5-45
5.6.2.3	IDEF Standards	5-49
5.6.2.4	Explicit Models Design	5-50
5.6.2.5	Plan Recognition	5-52
5.6.2.6	Feedback	5-53
5.6.2.7	Perceptual Control Theory	5-54
5.6.2.8	Help System Goals and Sub-Goals	5-55
5.6.2.9	Software Agent Paradigm	5-55
5.6.2.10	Hierarchical Goal Analysis (HGA) of Tasks in the Help System	5-57
5.6.2.11	Ecological Interface Design	5-57
5.6.2.12	Integrated Methodology for Help System Design	5-57
5.6.2.13	Help System Design Methodology	5-58
5.6.2.14	The Five-Part Taxonomy for Plan Recognition	5-60
5.6.2.15	The Five-Part Taxonomy for Plan Generation	5-62
5.6.2.16	Plans for Providing Help	5-64
5.6.2.17	Control Loop Design	5-66
5.6.2.18	Objects as Intelligent Agents	5-66
5.6.2.19	The PACT Approach and Automation Levels	5-67
5.6.2.20	References	5-68
5.6.3	Autonomous Decision Making for an Underwater Unmanned Vehicle	5-69
5.6.3.1	Underwater Unmanned Vehicles	5-69
5.6.3.2	Envisaged Theatre of Operations for Military UUVs	5-69
5.6.3.3	Approach to Automation and Decision Making	5-70

5.6.3.4	Multi-Agent System Representation	5-74
5.6.3.5	Autonomous Underwater Decision Making	5-75
5.6.3.6	Conclusions	5-78
5.6.3.7	References	5-78

Chapter 6 – Advanced UMV Operator Interfaces 6-1

6.1	Introduction	6-1
6.2	User-Centered Design for UMV Control	6-2
6.3	Guidelines and Gaps	6-4
6.3.1	Pre-Requisites to Selecting Human Interface Devices	6-4
6.3.2	Standards/Methodologies/Best Practice and Gaps	6-5
6.3.3	References for Guidelines and Gaps	6-7
6.4	Data Input Technologies	6-7
6.4.1	Manual Input Devices	6-7
6.4.1.1	Description of Technology	6-7
6.4.1.2	Actual or Potential Applications to UMVs	6-8
6.4.1.3	Technology Maturity, Challenges, and Unresolved Issues	6-8
6.4.1.4	References for Manual Input Devices	6-9
6.4.2	Speech Recognition Systems	6-10
6.4.2.1	Description of Technology	6-10
6.4.2.2	Actual or Potential Applications to UMVs	6-11
6.4.2.3	Technology Maturity, Challenges, and Unresolved Issues	6-14
6.4.2.4	References for Speech Technology	6-14
6.4.3	Additional Alternative Input Devices	6-17
6.4.3.1	Gesture-Based Control	6-17
6.4.3.2	Gaze-Based Control	6-18
6.4.3.3	Electromyographic (EMG)-Based Control	6-18
6.4.3.4	Electroencephalographic (EEG)-Based Control	6-19
6.4.3.5	Multi-Modal Input Design	6-19
6.4.3.6	References for Additional Alternative Input Devices	6-19
6.5	Data Display Technologies	6-21
6.5.1	Head-Mounted Displays	6-21
6.5.1.1	Description of Technology	6-21
6.5.1.2	Actual or Potential Application to UMVs	6-22
6.5.1.3	Technology Maturity, Challenges, and Unresolved Issues	6-25
6.5.1.4	References for Head-Mounted Displays	6-27
6.5.2	Augmented/Mixed Reality Technology	6-30
6.5.2.1	Description of Technology	6-31
6.5.2.2	Actual or Potential Application to UMVs	6-36
6.5.2.3	Technology Maturity, Challenges, and Unresolved Issues	6-37
6.5.2.4	References for Augmented/Mixed Reality Technology	6-38
6.5.3	3D Visual Displays	6-39
6.5.3.1	Description of Technology	6-40
6.5.3.2	Actual or Potential Application to UMVs	6-49
6.5.3.3	Technology Maturity, Challenges, and Unresolved Issues	6-52
6.5.3.4	References for 3D Visual Displays	6-52

6.5.4	Spatial Audio Displays	6-54
6.5.4.1	Description of Technology	6-54
6.5.4.2	Actual or Potential Application to UMs	6-57
6.5.4.3	Technology Maturity, Challenges, and Unresolved Issues	6-59
6.5.4.4	References for Spatial Audio Displays	6-60
6.5.5	Haptic Display Technology	6-62
6.5.5.1	Description of Technology	6-62
6.5.5.2	Actual or Potential Application to UMs	6-63
6.5.5.3	Technology Maturity, Challenges, and Unresolved Issues	6-65
6.5.5.4	References for Haptic Display Technology	6-65
6.6	Interface Issues for Multi-UMV Supervisory Control	6-68
6.6.1	Implications of Automation/Autonomy	6-68
6.6.1.1	What is Automation and Supervisory Control?	6-68
6.6.1.2	Levels of Automation Specific to UMs	6-69
6.6.1.3	Automation: A Double-Edged Sword	6-71
6.6.1.4	Philosophies and Methodologies	6-74
6.6.1.5	Interface Implications of Automation	6-75
6.6.1.6	Research Issues	6-76
6.6.1.7	References for Implications of Automation/Autonomy	6-77
6.6.2	Control/Display Interfaces for Decision Support	6-78
6.6.2.1	Methodology for Decision Support Interface (DSI) Survey	6-79
6.6.2.2	Decision Support Interfaces: Classification	6-79
6.6.2.3	Decision Support Interface Survey: Lessons Learned	6-81
6.6.2.4	Survey Implications on UMV Supervisory Control	6-84
6.6.2.5	References for Decision Support Control/Display Interfaces	6-84
6.7	Additional Considerations for UMV Interfaces	6-86
6.7.1	Scale of UMV Operator Interface	6-86
6.7.1.1	Man-Portable Platforms	6-86
6.7.1.2	Restricted-Space Platforms	6-87
6.7.1.3	Large-Space Platforms	6-88
6.7.1.4	References for Scale of UMV Operator Interface	6-89
6.7.2	UMV Operation from Moving Platforms	6-89
6.7.2.1	Physical Ergonomic Aspects	6-90
6.7.2.2	Manned-Unmanned UAV Teaming from Air-Based Control Station	6-94
6.7.2.3	References for UMV Operation from Moving Platforms	6-96
6.7.3	Other Issues: Latency, Trust, Bandwidth	6-97
6.7.3.1	Latency	6-97
6.7.3.2	Trust	6-98
6.7.3.3	Bandwidth and Update Rate	6-99
6.7.3.4	References for Other Issues	6-100
6.8	Summary	6-101

Chapter 7 – Human Automation Integration **7-1**

7.1	Introduction	7-1
7.1.1	Problems with Supervisory Control Tasks	7-1
7.1.2	Function Allocation	7-2

7.1.3	Levels of Automation	7-2
7.1.4	Pilots Associate Levels of Autonomy	7-2
7.1.5	Cognitive Cockpit PACT	7-2
7.1.6	UAV/UCAV Autonomy	7-2
7.1.7	Multi-Agent Adjustable Autonomy	7-3
7.2	Automation and Human Performance	7-3
7.2.1	Humans and Unmanned Military Vehicle	7-3
7.2.2	Human Factors and Automation	7-5
7.2.3	Recommendations	7-9
7.2.4	References	7-11
7.3	Human Automation Integration with Contractual Autonomy	7-12
7.3.1	Introduction	7-12
7.3.1.1	Function Allocation	7-12
7.3.1.2	Automation Reliability, Trust and Use	7-13
7.3.1.3	Trustworthy Levels of Automation	7-14
7.3.2	Contractual Autonomy	7-15
7.3.2.1	Pilot Authorisation and Control of Tasks	7-15
7.3.2.2	PACT Evaluation	7-19
7.3.3	Supervisory Control with Adjustable Autonomy	7-22
7.3.4	Conclusions	7-24
7.3.5	References	7-25
7.4	Adaptive Automation for Robotic Military Systems	7-29
7.4.1	Introduction	7-29
7.4.2	Human Performance Issues for Automated Systems	7-30
7.4.2.1	Adaptive Principles	7-33
7.4.3	Some Characteristics of Adaptive Automation Systems	7-34
7.4.3.1	Invocation Methods	7-34
7.4.3.2	Adaptive and Adaptable Systems	7-34
7.4.3.3	Human Interaction with Adaptive Systems	7-36
7.4.4	Physiological Measurement Techniques	7-37
7.4.4.1	Heart Rate and Heart Rate Variability	7-40
7.4.4.2	Electrocortical Activity	7-40
7.4.4.3	Blood Flow	7-41
7.4.4.4	Hybrid Measures	7-43
7.4.4.5	Measurement Conclusions	7-43
7.4.5	General Conclusions	7-44
7.4.6	References	7-44
7.5	Designing for Flexible Human-Automation Interaction: Playbooks for Supervisory Control	7-49
7.5.1	Intermediate Automation Levels-Costs of Automation Extremes	7-50
7.5.2	Tradeoff Space for Effects of Automation Level	7-52
7.5.2.1	Flexible Automation Levels	7-54
7.5.2.2	Characterizing Automation Levels	7-54
7.5.2.3	Prior Automation Level Spectra	7-54
7.5.2.4	Extending Automation Levels	7-56
7.5.2.5	Using Extended Automation Levels in Design	7-57
7.5.3	References	7-58

7.6	Delegation Architectures: Playbooks and Policy for Keeping Operators in Charge	7-63
7.6.1	UMV Control as Human-Automation Delegation	7-63
7.6.2	Types of Delegation	7-64
7.6.2.1	Playbook – Delegation of Goals, Plans and Constraints	7-65
7.6.2.2	Policy – Delegation via Abstract Value Statements	7-68
7.6.3	Conclusions and Future Work	7-71
7.6.4	Acknowledgements	7-72
7.6.5	References	7-72
7.7	Modelling Multi-Layered Control: Application of the Extended Control Model to the Analysis of UAV Scenarios	7-73
7.7.1	Introduction	7-73
7.7.1.1	Control as a Cognitive Engineering Problem	7-73
7.7.1.2	Bottom-Up Function Allocation	7-75
7.7.1.3	Top-Down Function Allocation	7-76
7.7.1.4	Layers of Control	7-76
7.7.1.5	Control and Models	7-77
7.7.1.6	Requisite Variety as Layers of Control	7-77
7.7.2	Contextual Control Models (COCOM)	7-78
7.7.2.1	Dynamic Control – COCOM	7-78
7.7.2.2	Extended Control Model (ECOM)	7-79
7.7.2.3	ECOM Structure and Parameters	7-81
7.7.3	Autonomous Control Level Framework	7-82
7.7.3.1	Levels of Autonomy	7-83
7.7.3.2	Individuals, Groups, Swarms	7-84
7.7.3.3	Mission Type and Autonomy	7-84
7.7.4	Analysis of UAV Scenarios	7-88
7.7.4.1	Description of Common Tasks	7-89
7.7.4.2	Description of Specific Tasks	7-90
7.7.5	Control, Automation and Views	7-92
7.7.5.1	Control and Time	7-92
7.7.6	Conclusions	7-93
7.7.6.1	Effects of Automation on Common and Specific Tasks	7-93
7.7.6.2	The Way Ahead?	7-94
7.7.7	References	7-95
7.8	Synthesizing Perspective – Supervisory Control and Decision Support Concepts	7-97
7.8.1	Uninhabited Aerial Vehicles	7-97
7.8.1.1	Factor 1: Advanced UAV Operator Control/Display Interface Technologies	7-98
7.8.1.2	Factor 2: Supervisory Control and Decision Support Concepts	7-99
7.8.1.3	Factor 3: Trust and Levels of Automation	7-101
7.8.2	Adaptive Automation	7-102
7.8.3	Putting It Together	7-103
7.8.4	Levels of Automation Within the Air Vehicle	7-105
7.8.5	Conclusion	7-106
7.8.6	References	7-106

Chapter 8 – Conclusions and Summary

8-1

8.1	Issue 1: Human Authority and Responsibility in Dealing with UMs	8-1
8.2	Issue 2: The Role of Human Operators with Advanced Automated and Intelligent UM Systems	8-2
8.3	Issue 3: Interoperability of UM Systems	8-3
8.4	Issue 4: Control Station Design	8-4
8.5	Issue 5: Operator Selection and Training	8-6
8.6	Summary	8-7

List of Figures

Figure		Page
Figure 2-1	NATO Air Command and Control System – NACCS	2-24
Figure 2-2	Peace Enforcement – Peace Support Operations at COMAO Level	2-32
Figure 2-3	Integration of UAV Assets in PSO COMAO	2-35
Figure 2-4	Illustration of Composite Scenario Task Links	2-41
Figure A3-1.1	Relation of User System Interaction	3-30
Figure A3-1.2	Taxonomy of Human-Machine Interaction	3-32
Figure 4-1	Comparison of Tactical Situation Displays with Unfused and Fused Data	4-11
Figure 4-2	Time Delays	4-15
Figure 4-3	Levels of UAV Interoperability and the Respective Communication Links	4-28
Figure 4-4	Functional Transfer and Time Transfer of the UAV during Different Mission Phases	4-29
Figure 4-5	Anticipated Results Showing that Performance is Directly Related to JSI	4-53
Figure 4-6	JSI versus Performance Results	4-53
Figure 4-7	Basic Architecture of an Embedded Training System	4-63
Figure 5-1	Scenario for Multi-Ship Air-to-Ground Attack Mission	5-3
Figure 5-2	Possible Characteristics in Future UAV Deployment – Substitution and/or Supplementation	5-4
Figure 5-3	Concept of Work System	5-5
Figure 5-4	Manual and Supervisory Control	5-6
Figure 5-5	Model of Human Manual and Supervisory Control	5-7
Figure 5-6	Conventional Guidance and Control System (Manned A/C)	5-8
Figure 5-7	Conventional Guidance and Control System (Unmanned A/C)	5-9
Figure 5-8	Organisational Structure of Conventionally, i.e. Hierarchically Automated Human-Machine Systems	5-10
Figure 5-9	Operator Overload Caused by Conventional Automation	5-11
Figure 5-10	Shortfalls with Conventional Automation	5-12
Figure 5-11	Perspectives of Future Automation	5-13
Figure 5-12	Co-operative Structure of Human-Machine Systems with Advanced Automation	5-14
Figure 5-13	Artificial Cognitive Unit (ACU) Mimicking Human Operator in a “Work System”	5-15
Figure 5-14	Comparison between Automatic and Autonomous Mission Accomplishment (Framed Elements Form Work System)	5-16
Figure 5-15	Work System with ACU in Configuration “Cognitive Automation as Part of Operation-Assisting Means”	5-17
Figure 5-16	Work System with ACU in Configuration “Co-operative Automation”	5-19

Figure 5-17	Technological Challenges in Advanced Automation	5-20
Figure 5-18	Modelling Behaviour or Processing	5-23
Figure 5-19	Rasmussen's Model of Human Operator's Performance Levels Linked to Environment	5-24
Figure 5-20	Model of Human Behaviour Motivated by Control Theory (i.e., Transfer Function)	5-26
Figure 5-21	Model of Human Processing Motivated by Information Technology	5-26
Figure 5-22	The Model Human Processor Adapted from CMN-Model	5-26
Figure 5-23	The Recognise-Act Cycle	5-27
Figure 5-24	Architecture of a Rule-Based System (i.e., Production System)	5-27
Figure 5-25	Conventional and Cognitive Automation Explained by Rasmussen's Model of Human Performance	5-30
Figure 5-26	The Cognitive Process	5-31
Figure 5-27	Representing Multiple Capabilities on Basis of the Cognitive Process	5-32
Figure 5-28	Method of Cognitive Systems' Development	5-34
Figure 5-29	COSA – Cognitive System Architecture	5-35
Figure 5-30	Recommended Applications of AI Method	5-41
Figure 5-31	Cognitive Co-operation and Human vs. Automation Control	5-70
Figure 5-32	Leveraging Autonomy through Cognitive Automation	5-71
Figure 5-33	Transition from Manned, through Current Unmanned, to Semi-Autonomous Underwater Vehicle	5-72
Figure 5-34	Decision Ladder Framework for Task Decomposition	5-73
Figure 5-35	Possible PACT Contract Levels for a UUV Mission	5-74
Figure 5-36	Tools and Techniques Drawn upon in the DSTL UCUV Work	5-76
Figure 6-1	Alchemy 2 Experimentation System	6-6
Figure 6-2	NIST Speech Recognition Benchmark Test History	6-11
Figure 6-3	Examples of HMDs	6-21
Figure 6-4	Dome Projection in which the Camera Direction is Head-Coupled, and the Operator Receives High Quality Proprioceptive Feedback on Camera Viewing Direction	6-23
Figure 6-5	UAV Workstation with Head-Coupled HMD and Stationary CRT Camera Displays	6-24
Figure 6-6	A Typical Interface Presents All Sensor Readings Side by Side	6-31
Figure 6-7	Integrated Display of Video, Range Readings, and Robot Representation	6-31
Figure 6-8	Representing the Pose of a Panning Camera	6-32
Figure 6-9	Depicting Camera Pose May Require a Perspective Change	6-32
Figure 6-10	The Chase Perspective for a UAV	6-33
Figure 6-11	Rotating the Video Supports the Ground-Based Perspective of the Remote Operator	6-34
Figure 6-12	An Occupancy Grid Map Can be Used as the Basis for Navigation	6-35
Figure 6-13	Augmenting a Terrain Map with Symbology Can Better Support Navigation and Sensor Management	6-35

Figure 6-14	UAV Locations Required to Support Low Ground Speed, Complete Coverage by a Camera Footprint Spiral	6-37
Figure 6-15	The Main Display	6-41
Figure 6-16	Overview of the Investigated Display Types	6-42
Figure 6-17	Target Acquisition Time as a Function of Two Dimensional (2-D) and Three Dimensional (3D) Display Type and Initial Position of the Target Aircraft, Averaged Across Participants	6-43
Figure 6-18	Example of a 3D Perspective Display	6-44
Figure 6-19	Examples of the Different Perspectives from which the Tactical Space Can be Viewed	6-45
Figure 6-20	The Experimental Transparent 3D Setup at TNO Human Factors	6-47
Figure 6-21	Data Substantiating the Claim that Accommodation (A) and Motion Parallax (P) Substantially Influences the Ease of Depth Perception when the Depth Gradient is Large	6-48
Figure 6-22	The Effect of Additive and Subtractive Transparency: the Colours Combine, Easily Causing Confusion	6-49
Figure 6-23	The Left Panel Shows the 2D Map with the Position of the UAV in the Center	6-50
Figure 6-24	Percentage of Inspected Areas as a Function of 3D Map and the Quality of Camera Images	6-51
Figure 6-25	Subjective Effort Rating as a Function of Quality of the Camera Images and 3D Map	6-51
Figure 6-26	Example Tactile Display (Tactile Waist Belt Clearly Showing the Vibration Elements)	6-63
Figure 6-27	Example of a Tactile Torso Display Used in Helicopter Orientation Studies	6-63
Figure 6-28	Tactile Wrist Pads as High Priority Alert Cue	6-64
Figure 6-29	Levels of Automation	6-70
Figure 6-30	Levels of Automation, U.S. Army Science Board	6-70
Figure 6-31	PCE Display Representation as an Overlay on a Radar Display	6-83
Figure 6-32	Example of Man-Portable Control Station	6-86
Figure 6-33	Example of Restricted-Space Platform	6-87
Figure 6-34	Example of Large-Space Platform – A Data Wall at U.S. Air Force Research Laboratory	6-88
Figure 6-35	An Example of a Digital Human Modelling System: A Manikin in a CAD Model of the F16	6-91
Figure 6-36	A Soldier Equipped with Various Portable Systems for Advanced Field Operations	6-93
Figure 6-37	Angular Error in Indicating an Object Location for the Six Question Types	6-95
Figure 6-38	Time to Target Identifications for the Six Display Configurations	6-96
Figure 6-39	Trust in ATM Context	6-99
Figure 7-1	Pact Progression of Operator Authority and Computer Autonomy	7-17
Figure 7-2	Task Network of Functions and Tasks Set to Pact Contract Levels	7-18
Figure 7-3	Control Task Analysis for PACT Level 3 Assisted In Support	7-20

Figure 7-4	Cognitive Load Estimates for PACT Levels	7-21
Figure 7-5	PACT Enabling Automation Reliability, Trust and Use	7-24
Figure 7-6	Human-Automation Taxonomy with Rows Representing Degree of Automation and Columns Processing Functions	7-30
Figure 7-7	Example of a Closed Loop Adaptation for A – Automated, A/M – Automated/Manual, and M – Manual Task Sets	7-33
Figure 7-8	The Tradeoff Relationship between System Competency, Human Workload and Unpredictability	7-52
Figure 7-9	A Tasking Interface Provides Flexibility Within the Tradeoff Space	7-53
Figure 7-10	Levels of Automation by Information Processing Phase for Two Systems	7-56
Figure 7-11	General Playbook Architecture	7-65
Figure 7-12	Prototype Playbook Interface for UCAV Mission Planning	7-66
Figure 7-13	Representation of a Policy for Network Bandwidth Prioritization	7-70
Figure 7-14	Cross Echelon Policy Application and Resolution	7-71
Figure 7-15	The Basic Construct-Action-Event Cycle	7-79
Figure 7-16	The Extended Control Model (ECOM)	7-81
Figure 7-17	DOD UAV Roadmap 2000	7-83
Figure 7-18	Revised ACL Description	7-87
Figure 7-19	Predator Operator Station and Dragon Eye Operator Station	7-98
Figure 7-20	Display Concepts	7-98
Figure 7-21	Operator-UAV System Diagram	7-100
Figure 7-22	Systems Authority Concepts	7-101
Figure 7-23	Adaptive Automation System Diagram	7-102
Figure 7-24	LOA Taxonomy for Human-Computer Performance in Dynamic, Multi-Task Scenarios	7-104
Figure 7-25	Aircraft Control Levels	7-105

List of Tables

Table		Page
Table 2-1	Summary of UAV Classes, Roles and Control	2-14
Table 2-2	Summary of UUV Missions and Environments	2-21
Table 2-3	Composite Scenario Tasks	2-39
Table 3-1	Survey Questions	3-6
Table 3-2	Survey Results	3-16
Table A3-1.1	List of Databases Searched	3-22
Table A3-1.2	Numbers of Papers in Different Research Domain	3-23
Table A3-1.3	Categorization of Literature Reviewed in Detail	3-23
Table A3-5.1	Critical Differences between Human-Machine and Multiple Agent Interaction	3-40
Table A3-7.1	Response of ‘System Process / Task Organisational Model for HF V&V’ to Questions	3-48
Table 4-1	JSI versus Measured Variables	4-54
Table 4-2	Measured Variables versus Assessed Performance	4-54
Table 4-3	Summary of Characteristics that Affect how UUVs are Employed Depending on the Mission Context	4-58
Table 5-1	Likely UAV or UCAV Mission Types	5-37
Table 5-2	Relative Merits of AI Techniques when Applied to UAV Mission Management Tasks	5-39
Table 5-3	Recommended AI Techniques for Identified UAV Autonomy Requirements, and Mapping to Processes	5-40
Table 5-4	PACT Levels of Autonomy	5-68
Table 6-1	A Scale of Degrees of Automation	6-68
Table 6-2	Levels of Automation of Decision and Action Selection	6-69
Table 6-3	Levels of Interoperability	6-71
Table 6-4	Human-Centered Automation Guidelines	6-74
Table 7-1	Evaluation of the Application of Automation on Unmanned Military Vehicles (UMVs)	7-7
Table 7-2	Bonner-Taylor PACT System	7-16
Table 7-3	Adjustable Autonomy Levels for Intelligent Multi-Agent Systems	7-23
Table 7-4	Matrix of Physiological Measures – Advantages and Disadvantages	7-39
Table 7-5	Levels of Automation	7-55
Table 7-6	Supported Delegation Actions and Methods	7-64

Table 7-7	Functional Characteristics of ECOM Layers	7-82
Table 7-8	A Possible Two-Dimensional Description of Autonomous Control Levels	7-85
Table 7-9	Relations between ECOM and the Revised ACL Description	7-86
Table 7-10	Overall Description of UAV Scenario	7-88
Table 7-11	Common and Specific Tasks in the UAV Scenario	7-89
Table 7-12	ECOM Characterisation of Common Mission Tasks	7-90
Table 7-13	ECOM Characterisation of Specific Mission Tasks	7-91
Table 7-14	Relations between Control Layers and Process Views	7-92

Contributing Authors

Mr. Michael Barnes
US Army Research Laboratory
Human Research and Engineering Directorate
Ft Huachuca, Arizona
United States
Email: michael.barnes@hua.army.mil

Mr. Timothy Barry
General Dynamics AIS
2255 H Street, Building 248
Wright-Patterson Air Force Base, Ohio 45433
United States
Email: timothy.barry@wpafb.af.mil

Mr. G. Scott Boucek
The Boeing Company
P.O. Box 3707 MC 13-60
Seattle, Washington 98124-2207
United States
Email: scott.boucek@boeing.com

Ms. Gloria Calhoun
United States Air Force
2255 H Street
Wright-Patterson Air Force Base, Ohio 45433
United States
Email: gloria.calhoun@wpafb.af.mil

Lt. Cdr. A. Graham Carver
Royal Navy, Winfrith Technology Centre
EC(UWB) RLO, Dstl Winfrith, A32/N15
Dorchester, Dorset DT2 8WX
United Kingdom
Email: gcarver@dstl.gov.uk

Mr. Mike Chamberlin
QinetiQ Ltd., Room 2007, A5 Building
Cody Technology Park, Ively Road
Farnborough, Hampshire GU14 0LX
United Kingdom
Email: MRCHAMBERLIN@qinetiq.com

Mr. Paul Clark
QinetiQ Ltd, Capability Support Division
Cody Technology Park
Farnborough, Hampshire GU14 0LX
United Kingdom
Email: JPCLARK@qinetiq.com

Dr. Keryl Cosenzo
US Army Research Laboratory
Human Research and Engineering Directorate
Ft Huachuca, Arizona
United States
Email: kcosenzo@arl.army.mil

Dr. Antoine de Reus
National Aerospace Laboratory
P.O. Box 90502
1006 BM Amsterdam
The Netherlands
Email: dereus@nlr.nl

Dr. Mark Draper
United States Air Force
2255 H Street
Wright-Patterson Air Force Base, Ohio 45433
United States
Email: mark.draper@wpafb.af.mil

Dr. Jack Edwards
AI Management and Development Corporation
206 Keewatin Avenue
Toronto, Ontario M4P 1Z8
Canada
Email: jle2@sympatico.ca

Dr. Philip Farrell
Canadian Forces Experimentation Centre
National Defence HQ (Shirley's Bay)
101 Colonel By Drive
Ottawa, Ontario K1A 0K2
Canada
Email: phil.farrell@drdc-rddc.qc.ca

Dr. Scott Galster
United States Air Force
2255 H Street
Wright-Patterson Air Force Base, Ohio 45433
United States
Email: Scott.Galster@wpafb.af.mil

Mr. John Gersh
Johns Hopkins University
11100 Johns Hopkins Road
Laurel, Maryland 20723-6099
United States
Email: john.gersh@jhuapl.edu

Dr. Michael A. Goodrich
3361 TMCB, Brigham Young University
Provo, Utah 84602
United States
Email: mike@cs.byu.edu

Major Armand Goossens
Royal Netherlands Air Force
The Hague
The Netherlands
Email: aahe.goossens2@mindef.nl

Dr. David Graeber
The Boeing Company
P.O. Box 3707 MC 4C-82
Seattle, Washington 98124-2207
United States
Email: david.a.graeber@boeing.com

Professor Erik Hollnagel
Industrial Safety Chair
Ecole des Mines de Paris – Pôle Cindyniques
Rue Claude Daunesse, BP 207
06904 Sophia Antipolis Cedex
France
Email: erik.hollnagel@cindy.ensmp.fr

Dr. Chris Jansen
TNO Defence, Security and Safety
Kampweg 5, P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: chris.jansen@tno.nl

Wg Cdr P.D. (Chaz) Kennett
Royal Air Force
Joint Services Command and Staff College
Defence Academy, Watchfield Road
Swindon, Wilts SN6 8TS
United Kingdom

Dr. Ir. Judith Kessens
TNO Defence, Security and Safety
Kampweg 5, P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: judith.kessens@tno.nl

Dr. Frank Kooi
TNO Defence, Security and Safety
Kampweg 5, P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: frank.kooi@tno.nl

Mr. Brice Kovacs
Dassault Aviation / IMASSA
78, Quai Marcel Dassault – Cedex 300
92552 St. Cloud Cedex
France
Email: Brice.kovacs@dassault-aviation.fr

Dr. Anna Langhorne
University of Dayton
Dept of Communications
300 College Park
Dayton, Ohio 45469-1410
United States
Email: Anna.Langhorne@notes.udayton.edu

Lt. Austen Lefebvre
United States Air Force
2255 H Street
Wright-Patterson Air Force Base
Ohio 45433
United States
Email: Austen.Lefebvre@wpafb.af.mil

Mr. Ian MacLeod
Defence College of Management and
Technology
UK Defence Academy
Shrivenham
United Kingdom
Email: house@farmparret.fsnet.co.uk

Dr. Chris Miller
Smart Information Flow Technologies, Inc.
1272 Raymond Ave.
Saint Paul, Minnesota
United States
Email: cmiller@sift.info

Dr. Steve Murray (PL – BS)
SPAWARSYSCEN 2374
53475 Strothe Road
Room 231
San Diego, California 92152-6343
United States
Email: steven.a.murray@navy.mil

Lt. Jeremy Nelson
United States Air Force
2255 H Street
Wright-Patterson Air Force Base
Ohio 45433
United States
Email: jeremy.nelson@wpafb.af.mil

Dr. Curtis W. Nielsen
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, Idaho 83415-2220
United States
Email: curtisen@gmail.com

Dr. Glenn Osga
Space and Naval Warfare Systems Center
San Diego, California
United States
Email: glenn.osga@navy.mil

Mr. A. Oudenhuijzen
TNO Defence, Security and Safety
Kampweg 5
P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: aernout.oudenhuijzen@tno.nl

Dr. Raja Parasuraman
George Mason University
Department of Psychology
4400 University Dr MS3F5
Fairfax, Virginia 22030
United States
Email: rparasur@gmu.edu

Mr. Morgan Quigley
Stanford University
Room 124
Gates Building
353 Serra Mall
Stanford, California 94305
United States
Email: mquigley@cs.stanford.edu

Ms. Kelly Reischel
The Boeing Company
P.O. Box 3707 MC 87-98
Seattle, Washington 98124-2207
United States
Email: kelly.m.reischel@boeing.com

Dr. John Reising
Technical Adviser
Warfighter Interface Division
Wright-Patterson Air Force Base
Ohio 45424
United States
Email: john.reising@wpafb.af.mil

Mr. Christopher Richardson
The Boeing Company
P.O. Box 3707 MC 8J-65
Seattle, Washington 98124-2207
United States
Email: christopher.s.richardson2@boeing.com

Dr. Jan Joris Roessingh
National Aerospace Laboratory
P.O. Box 90502
1006 BM Amsterdam
The Netherlands
Email: roess@tiscali.nl

Prof. Dr.-Ing. Axel Schulte
Universität der Bundeswehr München
Fakultät für Luft- und Raumfahrttechnik
Institut für Systemdynamik und Flugmechanik
85577 Neubiberg
Germany
Email: Axel.Schulte@unibw.de

Mr. R. Jay Shively
Human Systems Integration Group Leader
Army/NASA Rotorcraft Division
Mail Stop 210-5
NASA-Ames Research Center
Moffett Field, California 94035
United States
Email: jshively@mail.arc.nasa.gov

Mr. Brian Simpson
2610 Seventh Street, Building 441
Wright-Patterson Air Force Base
Ohio 45433
United States
Email: Brian.Simpson@wpafb.af.mil

Capt. Glenn Smith
Director Personnel – Applied Research
National Defence Headquarters
Ottawa, Ontario K1A 0K2
Canada
Email: smith.ga@forces.gc.ca

Maj. Patrik Stensson
Swedish Air Force
Air Combat School / Development Department
Box 645
SE-751 27 Uppsala
Sweden
Email: patrik.stensson@f20.mil.se

Prof. Robert J. Stone
Director
Human Interface Technologies Team
Department of Electronic
Electrical & Computer Engineering
University of Birmingham
Edgbaston, Birmingham B15 2TT
United Kingdom
Email: r.j.stone@bham.ac.uk

Dr. Peter Svenmarck
Swedish Defence Research Agency (FOI)
Box 1165
58111 Linköping
Sweden
Email: peter.svenmarck@foi.se

Mr. Robert Taylor
Dstl Air Systems and Weapons Department
A2/G007, Ively Gate, Ively Road
Farnborough, Hampshire GU14 0LX
United Kingdom
Email: rmtaylor@dstl.gov.uk

Maj. Anthony Tvaryanas
311 HSW/PER
2485 Gillingham Drive
Brooks City-Base, Texas 78235
United States
Email: Anthony.Tvaryanas@brooks.af.mil

Dr. Ing. Leo van Breda
TNO Defence, Security and Safety
Kampweg 5
P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: leo.vanbreda@tno.nl

Dr. Jan van Delft
TNO Defence, Security and Safety
Kampweg 5
P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: jan.vandelft@tno.nl

Dr. Jan van Erp
TNO Defence, Security and Safety
Kampweg 5
P.O. Box 23
3769 DE Soesterberg
The Netherlands
Email: jan.vanerp@tno.nl

Mr. Menso van Sijll
National Aerospace Laboratory
Anthony Fokkerweg 2
1059 CM Amsterdam
The Netherlands
Email: sijll@nlr.nl

Dr. Mike Waters
Dstl Information Management Department
A2, Ively Gate, Ively Road
Farnborough, Hampshire GU14 0LX
United Kingdom
Email: mwaters@dstl.gov.uk

Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

(RTO-TR-HFM-078)

Executive Summary

A number of NATO countries are now using Uninhabited Military Vehicles (UMVs) to augment their manned forces, especially in performing tasks which are dull, dirty, or dangerous. Force augmentation issues relevant to the human operator exist on several levels, including individual UMV control station design, vehicle interoperability, and integration of UMVs with manned systems. Human interface issues associated with individual UMV control station design include guaranteeing appropriate situational awareness for the task, minimizing adverse effects of lengthy system time delays, establishing an optimum ratio of operators to vehicles, and providing effective information presentation and control strategies. UMV interoperability requires development of a standard set of control station design specifications/procedures/heuristics to cover the range of potential UMV operators/applications across military services and countries. Finally, for UMVs to be successful, they must be successfully integrated with manned systems so as to enhance the strength of the overall force. Human factors considerations in this area include how manned systems should best collaborate with UMVs, deconfliction concerns, and command and control issues.

Given the current progress of technological developments and operational concepts regarding UMVs, a strong and combined effort of NATO-countries is essential to resolve the unique human-system issues associated with augmenting the existing force with these vehicles. New principles for supporting the operator in such scenarios, and for collaboration between multiple operators in vehicles, need to be developed and evaluated.

The goal of this report is to assemble pertinent information concerning the factors that will increase NATO's successful operations through effective force augmentation with UMVs. By bringing this information together in one report, decision-makers and scientists will be able to consider the numerous factors that have to be taken into account for operators to successfully work with UMVs. These different factors are discussed in the following chapters: Scenarios and Military Relevance, Theoretical Frameworks, System of Systems, Artificial Cognition and Cooperative Automation, Controls and Displays, and Human Automation Integration. The diversity of the subjects illustrates the challenge of successfully integrating UMVs into NATO forces.

The paragraphs below give a short description of the key factors needed for successful integration.

Scenarios and Military Relevance. Modern warfare requires military capabilities that respond to the threat of conventional hostile force and to the challenges of asymmetric conflicts, where political and military success relies on effects-based targeting and operations. Important questions remain about what realistic effects can be expected to be achieved by UMVs in the uncertain, ambiguous and non-linear battle-space of the future, including how international law will interpret robotic warfare in the future. Since UMV technologies are expected to actually reduce human involvement in some tasks, it is not self evident why HF issues should warrant raised attention. Thus, the reasons for raising HF concerns are in need of review.

Theoretical Frameworks. Frameworks have been used to guide the design of technology, procedures, systems, and systems of systems. UMV systems will also require theoretical frameworks to inform the

design process. Most of the frameworks used in traditional manned systems can be applied to uninhabited systems. However, revisiting the theoretical frameworks discussion allows us to highlight aspects of the frameworks that are directly applicable to optimizing operator/vehicle ratios and interoperability of uninhabited systems. In the investigation we may also find an emerging theory or framework that is unique to UMV systems.

System of Systems. New system architectures designed for interoperability are being developed to integrate multiple platforms into a common mission control element, giving the war-fighter access to a large volume of real-time information. Resolving issues associated with connectivity, knowledge and action consistency, and transfer of control have taken center stage along with traditional Human Factors issues related to information management, information processing, decision aiding, levels of autonomy, command and control, manpower and skills, and training. To be successful, these issues must be addressed during the early stages of systems engineering to ensure proper human-centered development of UMV systems within a system-of-systems architecture.

Artificial Cognition and Cooperative Automation. This section describes a systems engineering framework which facilitates the definition of required automation functions and addresses the need for intelligent automation in order to guide uninhabited military vehicles. This framework is primarily based upon considerations of human performance and cognitive engineering. Taking a general and well accepted model of human cognition as a starting point, the issues of intelligent machine performance in decision-making, human-machine teamwork in a distributed system, and level of automation/system autonomy, in terms of allocation of functions and responsibilities, are discussed at a conceptual depth.

Controls and Displays. As application of automation technology to the UMV domain increases, the potential for unintentional side effects associated with highly automated systems needs to be considered. These include rapid and significant fluctuations in operator workload, loss of situational awareness, lack of perceived reliability, complacency, skill loss, and operator performance decrements. To truly have a human-centered approach when incorporating automation in UMV applications, it is necessary to employ well designed controls and displays – controls that enable efficient task completion and displays that keep the remote operator well-informed. A goal of the interface is to recreate some of the cues available in the world. Indeed, it could be said that the primary goal of the interface should be to reproduce the perceptual cues that are used by the operators in the real environment to perform the task.

Human Automation Integration. To a large extent, operators will interact with UMVs using supervisory control. In addition, UMVs will contain multi-agent associate software that enables adaptive and adjustable automation between the operator and the vehicle. By utilizing dynamic function allocation and various levels of automation, an architecture can be designed to create an efficient team between the operator and the vehicle. Research conducted by NATO team members has already demonstrated the employment of user knowledge acquisition to produce a practical, communicable set of assisted levels (At Call, Advisory, In Support, Direct Support) for variable and adaptive decision support/automation, supporting situational assessment, decision making and action.

Véhicules militaires sans pilote (UMV) : Questions relatives aux facteurs humains liés à l'augmentation des forces (RTO-TR-HFM-078)

Synthèse

Un certain nombre de nations de l'OTAN utilisent désormais des Véhicules militaires sans pilote (UMV) tout particulièrement pour l'accomplissement de tâches ennuyeuses, salissantes ou dangereuses, dans le but d'augmenter leurs moyens humains. Les questions, liées à l'augmentation des forces, qui concernent l'opérateur humain existent à plusieurs niveaux, parmi lesquels la conception de postes de commande d'UMV individuels, l'interopérabilité des véhicules, et l'intégration d'UMV avec des systèmes pilotés. Les notions d'interface humaine associées à la conception de postes de commande d'UMV individuels garantissent une connaissance de la situation adaptée à la tâche, la limitation des effets indésirables de la lenteur des systèmes, la détermination d'un rapport optimal opérateurs/véhicules, et la fourniture de stratégies de contrôle et d'une présentation d'informations efficaces. L'interopérabilité des UMV nécessite le développement d'une série normative de spécifications/de procédures/d'heuristique de conception de postes de commande, afin de couvrir la gamme des opérateurs/applications potentiels des UMV parmi les services militaires et les nations. Enfin, pour que les UMV réussissent, ils doivent être intégrés avec succès aux systèmes avec pilote, de façon à augmenter la puissance de l'ensemble de la force. Les considérations liées aux facteurs humains en ce domaine incluent la meilleure manière, pour les systèmes pilotés, de collaborer avec les UMV, les questions de déconfliction, et les problèmes de commandement et de contrôle.

Etant donné les progrès actuels des développements technologiques et des concepts opérationnels dans le domaine des UMV, un effort soutenu et combiné de la part des nations de l'OTAN est primordial pour résoudre les problèmes particuliers homme-système associés à l'augmentation des forces existantes à l'aide de ces véhicules. De nouveaux principes pour soutenir l'opérateur dans de tels scénarios, et pour la collaboration entre des opérateurs multiples dans les véhicules, doivent être développés et évalués.

L'objectif de ce rapport est de rassembler des informations pertinentes sur les facteurs qui augmenteront le nombre d'opérations réussies de l'OTAN grâce à l'accroissement effectif des forces par les UMV. En réunissant ces informations en un seul et même rapport, les décideurs et les scientifiques pourront réfléchir aux nombreux facteurs à prendre en considération pour que les opérateurs puissent travailler avec succès avec les UMV. Ces différents facteurs sont examinés dans les chapitres suivants : Scénarios et pertinence militaire, Cadres théoriques, Système de systèmes, Cognition artificielle et automatisation coopérative, Commandes et affichages, et Intégration homme-automatisation. La diversité des sujets illustre le défi que représente l'intégration réussie des UMV dans les forces de l'OTAN.

Les paragraphes ci-dessous décrivent brièvement les facteurs clés nécessaires à une intégration réussie.

Scénarios et pertinence militaire. La guerre moderne nécessite des moyens militaires qui répondent à la menace de forces hostiles conventionnelles et aux défis des conflits asymétriques, où le succès politique et militaire repose sur le choix des objectifs et des moyens de traitement et sur les opérations en fonction des effets. Des questions importantes demeurent quant aux effets réalistes que l'on peut espérer obtenir avec les UMV sur le champ de bataille incertain, ambigu et non linéaire du futur, y compris la manière dont le droit international traitera la guerre robotique dans le futur. Dans la mesure où l'on s'attend à ce que les

technologies des UMV réduisent en fait l'engagement humain pour certaines tâches, il n'est pas évident que les questions de FH justifient une attention soutenue. En conséquence, les raisons de soulever des problèmes de FH doivent être révisées.

Cadres théoriques. Des cadres ont été utilisés pour guider la conception de technologies, de procédures, de systèmes, et de systèmes de systèmes. Les systèmes d'UMV nécessiteront également des cadres théoriques pour renseigner le processus de conception. La plupart des cadres utilisés dans les systèmes pilotés traditionnels peuvent être appliqués aux systèmes sans pilote. Toutefois, revisiter la question des cadres théoriques nous permet de mettre en lumière des aspects de ces cadres qui sont directement applicables à l'optimisation des rapports opérateur/véhicule et de l'interopérabilité des systèmes sans pilote. Au cours de l'étude, nous pouvons aussi découvrir une théorie émergente ou un cadre particulier aux systèmes d'UMV.

Système de systèmes. De nouvelles architectures de systèmes conçues pour l'interopérabilité sont en train d'être développées pour intégrer les plates-formes multiples dans un organe de commande de mission commun, donnant au soldat la possibilité d'accéder à un volume important d'informations en temps réel. La résolution de problèmes liés à la connectivité, la cohérence des connaissances et des actions, et le transfert de commande occupent désormais le devant de la scène, aux côtés des problèmes traditionnels de Facteurs humains relatifs à la gestion et au traitement des informations, à l'aide à la décision, aux niveaux d'autonomie, au commandement et au contrôle, à la main d'œuvre et aux aptitudes, et à la formation. Pour réussir, ces questions doivent être abordées au cours des premiers stades d'ingénierie des systèmes afin de garantir un développement adapté, centré sur l'humain, des systèmes d'UMV au sein d'une architecture de système de systèmes.

Cognition artificielle et automatisation coopérative. Cette section décrit un cadre d'ingénierie de systèmes qui facilite la définition des fonctions d'automatisation requises et aborde la nécessité d'une automatisation intelligente pour guider les véhicules militaires sans pilote. Ce cadre est principalement fondé sur des considérations de performances humaines et d'ingénierie cognitive. En prenant comme point de départ un modèle général et largement admis de cognition humaine, les problèmes de performances des machines intelligentes dans la prise de décisions, le travail d'équipe homme-machine dans un système réparti, et le niveau d'automatisation/d'autonomie du système, en termes d'attribution des fonctions et des responsabilités, sont examinés à un niveau conceptuel.

Commandes et affichages. Avec l'augmentation de l'application de la technologie d'automatisation au domaine des UMV, la possibilité d'effets indésirables non intentionnels liés aux systèmes fortement automatisés doit être prise en compte. Cela comprend les fluctuations rapides et importantes de la charge de travail de l'opérateur, la perte de la connaissance de la situation, l'absence de fiabilité perçue, l'excès de confiance, la perte d'aptitudes, et les diminutions de performances de l'opérateur. Afin d'avoir une approche réellement centrée sur l'humain lors de l'intégration de l'automatisation dans les applications UMV, il est nécessaire d'utiliser des commandes et des affichages bien conçus – des commandes qui permettent l'exécution efficace des tâches, et des affichages qui maintiennent l'opérateur à distance bien informé. L'un des buts de l'interface est de recréer certains des repères disponibles dans le monde réel. En effet, on pourrait dire que l'objectif principal de l'interface devrait être de reproduire les repères sensoriels utilisés par les opérateurs en environnement réel pour l'accomplissement de la tâche.

Intégration homme-automatisation. Dans une large mesure, les opérateurs interagiront avec les UMV en utilisant un dispositif de surveillance. En outre, les UMV comprendront des logiciels associés multi-agents qui permettent l'automatisation adaptative et ajustable entre l'opérateur et le véhicule. Grâce à l'attribution de fonctions dynamiques et à divers niveaux d'automatisation, une architecture peut être conçue en vue de faire de l'opérateur et du véhicule une équipe efficace. Les recherches menées par les membres de l'équipe de l'OTAN ont déjà décrit l'utilisation de l'acquisition de connaissances de l'utilisateur en vue de produire une série pratique, communicable, de niveaux assistés (sur demande, consultatif, en appui, appui direct) pour l'aide à la décision/l'automatisation variables et adaptatives, soutenant l'évaluation de la situation, la prise de décision et l'action.

Chapter 1 – INTRODUCTION

Chapter Lead: R. Taylor

Contributors: J. Reising, R. Taylor

The terms of Reference (TOR) for the Task Group (TG) lists as its objective to seek to augment the force using uninhabited military vehicles (UMVs) by leveraging the potential advantages of UMVs to act as force multipliers. Since there are no truly uninhabited systems – operators will always be in the loop in some fashion – human factors issues become crucial to the successful operation of these systems. Force multiplication can be achieved by addressing the human factors issues and challenges shown below.

- Collaborative Work – Optimal Task Distribution;
- Virtual team performance;
- Manned/Unmanned collaboration;
- Interoperability;
- Flexible level of automation;
- Optimization of operator/vehicle ratio;
- Control Stations – Intelligent Operator Support;
- Operator functional state assessment;
- Intelligent adaptive interfaces;
- Cognitive cooperation; and
- Knowledge management systems.

After NATO/RTO approval of the TOR, the TG was formed. Seven countries agreed to participate: Canada, France, Germany, The Netherlands, Sweden, United Kingdom and United States.

1.1 THE ISSUES

Following some initial meetings, a crucial symposium was held in Leiden, The Netherlands to frame the issues to be addressed by the TG. The results of the symposium led to the following five key issues which form the basis of discussion in the final technical report:

- 1) Theoretical Frameworks;
- 2) System of Systems;
- 3) Cooperative Automation and Computational Intelligence;
- 4) Controls and Displays; and
- 5) Human-Automation Integration.

After subsequent meetings, a chapter on Scenarios and Military Relevance was added. With the addition of Introduction and Summary and Conclusions chapters, and the modification of some chapter titles, the technical report (TR) now contains the eight chapters listed below:

INTRODUCTION

- 1) Introduction
- 2) Scenarios and Military Relevance
- 3) Theoretical Frameworks
- 4) System of Systems
- 5) Artificial Cognition and Cooperative Automation
- 6) Controls and Displays
- 7) Human-Automation Integration
- 8) Summary and Conclusions

The objective of this Introduction is to give an overview of the key issues discussed in each of these chapters.

1.2 SCENARIOS AND MILITARY RELEVANCE

UMVs are enablers of military capability with clear endorsement at the highest level. Many NATO Nations have active programmes to develop and integrate UMV systems into the front line military force mix. UMVs are most commonly characterised as dealing well with “3D” tasks – dull, dirty and dangerous. They are used extensively in intelligence, surveillance and reconnaissance (ISR), roles affording persistence in the provision of critical information, without risking lives. Increasingly, they are being utilized for combat and support roles. Important questions remain about what realistic effects can be expected to be achieved by UMVs in the uncertain, ambiguous and non-linear battle-space of the future, including how international law will interpret robotic warfare in the future.

UMVs are used extensively to gather information in ISR roles for human interpretation. ISR information is inherently incomplete and uncertain. Fundamentally, computer-based information processing systems are limited in that they can not comprehend the meaning of information in human cognitive terms, e.g., apply knowledge, understand, feel truth, appreciate implications, judge consequences. Critical military judgment is needed to interpret the meaning of ISR information. Crucially, UMVs can not appreciate the effects of the use of lethal force. This lack of appreciation of lethal force consequences is one of the key issues why human factors are important military relevant issues with “unmanned” technologies. An example of this is illustrated in the use of autonomous UAVs. Autonomy is needed so that degraded communications, whether caused by sunspots or jamming, must not impair the aircraft functionality or the system’s ability to complete missions within the assigned rules of engagement (ROE). The example ROE given is the use of force only if authorized by the human operator. An excellent summarization of the ethical/moral issues utilizing UMVs in combat was discussed by Air Chief Marshall Sir Brian Burridge. (Reference 29 in Chapter 2)

“When we go into combat, we have got to be sure what we are doing is both legal and moral. I do not believe that, in future, even though technology will allow it, we will be allowed to indulge in robotic warfare. I simply do not see the international community regarding that as an appropriate way to fight. The notion of using UCAVs controlled from 10 time zones away to prosecute a battle is not something international law of the future will regard as acceptable. I think the notion of a person in the loop, the notion of positive ID, the notion of someone feeling the texture of what is going on in the battlespace, is going to be more and more prevalent..... Overall, I think robotic warfare drives you away from what I term as emotional connectivity with the battlespace. My view is that winning the hearts and minds battle with the indigenous population requires this emotional connectivity.”

Note: In this report, when referencing UUVs, the term “uninhabited” will be substituted for “unmanned” where appropriate, in recognition of the role of both women and men equally in serving our armed forces.

1.3 THEORETICAL FRAMEWORKS

Theoretical frameworks have been used to guide the design of technology, procedures, systems, and systems of systems. UUV systems will also require theoretical frameworks to inform the design process. Most of the frameworks used in traditional manned systems can be applied to uninhabited systems. However, revisiting the theoretical frameworks discussion allows us to highlight aspects of the frameworks that are directly applicable to optimizing operator/vehicle ratios and interoperability of uninhabited systems. In the investigation we may also find an emerging theory or framework that is unique to UUV systems.

The place for theory in design is as follows:

- Theory can be the starting point for design;
- Theory may identify the critical design decisions;
- Theory allows for a common taxonomy within and across systems;
- Theory helps track and maintain the aim throughout the system life cycle;
- Theory helps design system verification and validation; and
- Theory helps generate measures of effectiveness.

There are a number of theoretical frameworks that address operator/vehicle optimization and interoperability. Theoretical frameworks developed for operator-manned vehicle interaction can be applied to uninhabited systems when it comes to basic ergonomics, workstation design, task analysis, workload and situational awareness. In most cases, human-machine interaction theories apply regardless if humans are inside or outside of the vehicle, although ego- versus exo-centric frames of reference may become an issue specific to UUVs. Human-human interaction theories (i.e., social behaviour) might better describe operators who interact with vehicles as a team. Thus human-machine and human-human interaction theories are reasonable starting points for exploring operator/vehicle and interoperability optimization.

The choice of a framework for analysing and designing UUV systems may depend on the proposed solution. For example, if reducing the operator/vehicle ratio means going from three operators operating one vehicle to one operator operating three vehicles, then one can imagine the requirement for intelligent help and levels of automation. The theoretical framework will need to address the following aspects:

- Level of automation and time and cultural dependencies.
- Goal/constraint level interactions instead of action level interactions.
- Self-generating future plans.
- Environment and system unpredictability.
- Trust and system acceptability and predictability.
- Implications of truly autonomous (free will) systems.
- Animation and personification of machines.
- Self-awareness, environment awareness, and awareness of itself within its environment.

While the theory may be the starting point of the design, aspects of the design define the theoretical framework to be applied. There is some initial iteration and recursion in determining the theoretical framework; however this recursion should quickly converge so that the design can move forward.

1.4 SYSTEM OF SYSTEMS

Once dismissed as novel technology that would never be useful within a dynamic environment, UMs are being developed in greater numbers and growing sophistication as the modern military strives for greater persistence over the battlefield, more real-time intelligence, and the ability to strike heavily defended targets. New system architectures designed for interoperability are being developed to integrate multiple platforms into a common mission control element giving the war-fighter access to a large volume of real-time information. The end result is an entire set of new Human Factors related challenges facing developers to ensure successful human systems integration. Resolving issues associated with connectivity, knowledge and action consistency, and transfer of control have taken center stage along with traditional Human Factors issues related to information management, information processing, decision aiding, levels of autonomy, and command and control (C2).

As one example, consider manpower and skills, and training. The transfer of skills and knowledge, and the requirement for general skill and knowledge levels will contribute to force multiplication by drawing from an existing, broader pool of people that can operate UMs. There are also new challenges connected with embedded training. We clearly do not want to compromise safety by introducing virtual entities in a scenario; unsafe situations in response to virtual entities are simply unacceptable. Since displays can contain both real and virtual information at the same time, operators should always be aware which information is real and which is virtual. A potential implementation for symbols on a display is to give the virtual entities a dedicated supplementary tag. In the fighter embedded training system that was developed at NLR in The Netherlands, this is accomplished by attaching a small “v” to each virtual symbol on all displays where they can appear.

To be successful, these issues must be addressed during the early stages of systems engineering to ensure proper human-centered development of UM systems within a system-of-systems architecture. It begins with understanding the concept-of-operation in which UMs will operate and then identify mission system requirements. As Bruce Clough [Reference 26 in Chapter 7] correctly states, *“The hardest part of making a decision isn’t deciding, it’s knowing what to decide with.”* What is the situation and how best can decision aiding be applied? Clough continues with another lesson learned, *“Best autonomy method used is related to task to accomplish, there is no optimal method for any task.”*

Because there is no optimal method, it is critical that operators are kept in the autonomous UM and decision aid supervisory control loops. UMs are envisioned to operate in areas of uncertainty, making them subject to automation “brittleness”. Automation brittleness is the concept that automated decision-support algorithms are typically fixed in code in initial design phases, and therefore unable to resolve unforeseen circumstances. Higher levels of automation are ideal for rigid tasks that do not require flexibility in decision making and have a low probability of system failure. Conversely, higher levels of automation are not recommended for dynamic decision making environments like command and control and thus decision aids incorporating interactive sensitivity analysis are requisite because of the risks and the complexity of both the C2 domain system and the inability of decision aids to be perfectly reliable.

Following a disciplined Systems Engineering approach that combines top-down requirements development with a bottoms-up rapid prototyping capability should result in a human-centered design that is both optimal and credible. Using rapid prototyping tools that provide standard widgets, display templates, and auto-code

generation allows the user interface designer to produce concepts that can be evaluated early and often by the operator as well as integrated directly with the final mission control system.

1.5 ARTIFICIAL COGNITION AND COOPERATIVE AUTOMATION

One of the key proposed advances in UGV control is the integration of artificial cognition in the process of vehicle guidance and supervision. In particular, the idea of co-operative control, i.e., the co-operation between the human operator and automation, is very important. Human-automation integration can be viewed from two different standpoints. On the one hand, in the near term, the human has to be considered as the user of automation technology not always designed with the user as the center of the design. On the other hand, relative to the future, the consideration of human performance in the work processes suggests some unique approaches to automation and decision systems. These approaches reveal the potential of human-like behaving and cooperating machines (in the sense of rational behaviour) in certain given task domains. Another potential product is human-centred automation, promising significant performance advances, once introduced into a work place.

A major emphasis in current conventional automation is the paradigm of supervisory control. However, with regard to supervisory control of UGVs, the operator can experience a number of problems:

- Manual control of the inner loops may not be possible or desirable because of intolerable time delays in the data transmission with respect to the inner loop dynamics time constants. Thus, the remote operation relies heavily upon the availability, performance and integrity of some specific guidance functions.
- Insufficient downlink bandwidth and/or incomplete sensor coverage, with respect to the task, can cause what may be called “keyhole perspective” for the remote operator, potentially affecting the correctness or quality of his or her decisions.
- The availability of data link, i.e., the ability to monitor (via telemetry) or control (via telecommand) the vehicle remotely may be disturbed. As a result, no recognition of nor reaction to unexpected situations is possible any more on the human operator’s side.

In essence, with the increasing complexity of automation, the human operator is almost completely separated from the underlying process. The long term problem is loss of skills, i.e., erosion of competence. The human-out-of-the-loop problem has other implications in situations where operators almost fully rely upon the automation – any abnormal situation will inevitably cause human overload and possibly erroneous action.

One approach to solving these problems is to incorporate an advanced automation concept called an Artificial Cognitive Unit (ACU) as part of a work system. Advanced automation will not displace the human operator in a work system, but share the tasks in a close-partner work relationship. Task allocation will not be static, but may be adapted to the current situation’s needs. This includes the facilitation of redundancy in functions by at least a partial overlap in capabilities with respect to the task spectrum. The responsibility of automation (not necessarily authority) will be extended to the supervisory control level, i.e., automation will be enabled to perform certain tasks under consideration of the overall work system. Thereby, automation brittleness will be addressed. Coordination and communication with such an automated system will be supported on all performance levels, i.e., reaching from detailed low level information (reducing opacity of the machine solutions) up to abstract human-like information exchange on the supervisory level (addressing literalism of the automation). In general, this approach to cognitive coupling can be a contributing factor to the mitigation of the negative effects of automation complexity.

INTRODUCTION

As indicated above, supervision and co-operation as accomplishments of a machine system require special capabilities. These capabilities were combined within the notion of the ACU. Obviously, the performance feature of cognition is the core element which has to be dealt with in order to design such an ACU. From the point of view of the discipline of cognitive psychology human, i.e., natural cognition can be described by considering:

- Perception and allocation of attention,
- Knowledge representation and memory,
- Problem solving, reasoning and decision making,
- Language comprehension and its generation, and
- Learning and the development of expertise.

The availability of at least some of these aspects of cognition is the necessary pre-requisite to perform the supervisory control task with respect to the overall work task.

Within a particular work system, the ACU represents all the performance requirements found to be attributed to the human operator earlier on, i.e., the performance of decision-making, problem-solving and supervision in order to comply with the overall work task. The implication of advances in automation such as the ACU is to concentrate on the treatment of human and machine cognition as an inter-disciplinary approach based upon cognitive psychology and artificial intelligence as branch of information technology.

1.6 CONTROLS AND DISPLAYS

Even with rapid advances in computer processing, automation technology, and artificial intelligence methods, there remains a critical need for human involvement in order for UMVs to successfully perform their missions. The human provides unique strategic and innovative decision-making capabilities within complex, dynamic, and time sensitive situations. UMV operator performance and, by extension, the UMV operator control/display interface, will be even more critical to achieving anticipated new and increasingly complex UMV capabilities including close-coupled operations with manned systems, UMV interoperability, and military strike/combat operations. This chapter discusses a wide range of control devices. While buttons, levers, keyboards mice, trackballs, and joysticks are mentioned, more advanced input technologies such as speech recognition, touch pads, gesture- and gaze-based controls, receive the most attention. Physiological controls based on electromyographic and electroencephalographic signals are also discussed.

A variety of display technologies are also considered. Visual displays include: head-mounted and large wall-mounted, augmented/mixed reality, 3d stereoscopic and large tablet-like PDAs. Displays based on other senses take in spatial audio and haptic inputs.

Given that humans are to remain a key component of UMV systems for the foreseeable future, it is important to recognize the unique challenges levied upon the operator. These challenges include the effects of system time delays (both fixed and variable), bandwidth limitations (which can be intermittent), datalink degradations/dropouts, and the loss of the rich supply of multi-sensory information often afforded to onboard operators. With future highly automated UMV systems, issues also include functional allocation of tasks between the operator and the system, human vigilance decrements, 'clumsy automation', limited system flexibility, mode awareness, trust/acceptance issues, failure detection, and automation biases. However, it is also important to note that the physical separation of crew from vehicle might also offer some unique

benefits that should be exploited. Besides the obvious benefit to crew safety, it is quite likely that available bandwidth and the variety of available information sources might be, in certain cases, far greater for a geographically-separated UMV crew versus an onboard operator, potentially resulting in more situation awareness rather than less. This, of course, assumes that a well-designed operator interface exists that can rapidly filter and fuse this expanded information into intuitive displays, again underscoring the need to attend to operator interface issues to ensure maximal system performance.

It is also important to note that as technology advances; the role of the UMV operator must change as well. UMV operator interfaces should not be considered ‘one-size-fits-all’, but must be tailored to match the capabilities and limitations of the host system and intended mission. Most current UMVs require that operators have the capability to manually control the vehicle and activate state changes (i.e., direct tele-operation). Thus, operator interfaces for these vehicles can best leverage the numerous lessons learned from decades of inner-loop control design research, while applying novel interfaces to combat challenges that are uniquely associated with UMV operation.

With new, highly automated UMVs, the operator’s role is becoming more supervisory in nature, overseeing the automated activation of programmed events (e.g., making sure the appropriate event is activated at the appropriate time), managing changes to the automated mission plan, and making more strategic-level decisions. These operator interfaces must take into account issues associated with automation management, including vigilance effects, brittle/clumsy automation, sudden workload spikes, etc.

Continuing this trend beyond the current state-of-the-art, a vision exists for a new interface paradigm for controlling next generation UMVs. This envisioned interface system involves multiple semi-autonomous UMVs being controlled by a single supervisor. These UMVs will have the capability to make certain higher-order decisions, independent of operator input and pre-defined mission plans. This capability of the UMV ‘to decide’ constitutes a whole new set of challenges for operators, as they will be required to rapidly judge the appropriateness of these decisions and assess their impact on overall mission objectives, priorities, etc. Future operator interfaces will need controls and displays tailored for multi-UMV control and to allow the operator the capability to easily inspect/override the autonomous UMV decision-making logic. These interfaces will also need to provide information fusing/filtering algorithms, intelligent prioritization/cueing logic, and possibly some form of adaptive task allocation in response to rapidly changing events and/or workload levels.

1.7 HUMAN-AUTOMATION INTEGRATION

Many versions of future concept of operations (CONOPS) rely heavily on UMVs. However, adding more UMVs and having them perform more complex tasks will not be realized without augmenting the current structure of control. One way to achieve this augmentation is through the utilization of automation. Automation, if applied in a responsible and judicious manner, will enable the acquisition of capabilities that will be required to operate under near and far-term CONOPS.

However, one of the key questions is, exactly how will the automation be applied in a responsible and judicious manner? Automation is not a simple concept – it involves different kinds of operator control, function allocation between the operator and the automation, various levels of authority for the automation, and the use of intelligent agents (single or multiples) within the automation. All of these aspects have to be considered, both theoretically and practically, if we are to create optimal human-automation integration. Chapter 7 begins with a discussion of operator control and finishes with UAVs operating as autonomous

INTRODUCTION

swarms. In the near term operators will use supervisory control, but supervisory control is not without its own problems.

1.7.1 Problems with Supervisory Control Tasks

Supervisory control of vehicles deals with automated vehicle control functions to a large extent. The operator, who may observe the controlled process, acts as a manager who supervises the system and interacts with the automated system by performing corrective actions. It is known, however, that supervisory control systems have certain limitations in performance, either on the operator's side due to human capacity limitations or induced by deficiencies of the automation, causing human error intensified by the inability of the automation to perform on the higher level of problem-solving.

1.7.2 Function Allocation

Another consideration is who should do what? Both the operator and the automation have the capability to perform various functions. How do we decide to assign these functions to the operator or the automation, and once assigned how do we integrate the human and automation to work together optimally?

Consider the development of human roles and automation from the traditional “left-over principle”, through human engineering optimising compensatory principle with human monitoring (Fitts lists), to contemporary complementary principle arising from human-computer co-operation/collaboration. Now function allocation can be dynamic according to external system functions, efficiency and system boundary conditions.

1.7.3 Levels of Automation

Once you decide the allocation of the functions to the automation or the operator, then the question becomes; how much authority do you give to the automation to act on its own? Specifically, how much decision making authority do you give to the automation? These levels range from none to all. What are the guidelines to make this decision?

The term autonomy has been introduced to describe the bounding of functioning and decision authority of advanced automation and intelligent decision systems. Autonomy can be defined simply as the capability to make decisions. Thus, autonomy can be considered in terms of the freedom to make decisions, considering constraints on decision-making (limitations, boundaries, rules, regulations), decision-making abilities (authority, responsibility, competency), and the capability to make different kinds of decisions (classes, functions, levels).

For designing supervisory control, possible structures for the allocation of decision-making tasks between human and computers are complex (up to 10 levels), but some authors discuss four or five. These have been applied to stage models of human information processing functions (information acquisition, analysis, decision selection, action implementation). Ideas of levels of automation have been proposed to represent scales of delegation of tasks to automation, with implications for reliability, use and trust.

1.7.4 Multi-Agent Adjustable Autonomy

Dynamic adaptive and adjustable autonomy is proposed for multi-agent intelligent systems for distributed problem solving structures in complex dynamic environments. Agents have self-direction and goals with capability to form, modify or dissolve the agent organisation. Degree of autonomy becomes linked to

individual goals. Focus moves to the decision process for how a goal is pursued free from intervention, oversight or control by another agent. Autonomy with respect to goals is on a variable scale (consensus, master, local, command). Issues become rules for transfer of control, communication protocols, interaction styles, and cognitive strategies for reasoning with adjustable autonomy in operating context. An example of this concept is illustrated below in the discussion of UAVs operating as a swarm.

1.7.5 Levels of Automation within the Air Vehicle

As UAV control becomes more sophisticated, there will be intelligent software both in the operator's console as well as within the UAV itself. The airborne computing system enables 10 levels of autonomy called autonomous control levels (ACLs) within the UAV. One of the interesting things about ACLs five and higher, is that they refer to how the entire flight works together as a group, with the highest level being fully Autonomous Swarms where the vehicles are acting in concert with one another to achieve a common goal.

So, what does this have to do with UAVs? If a flight of UAVs could act as a swarm, instead of giving them explicit, detailed instructions on the location of surface-to-air missile batteries, for example, they could be directed to just loiter about a certain area of enemy territory and if they come across the missiles they could destroy them. Of course, they would be acting within the level of responsibility given to them by the human operator. Creating digital pheromones for UAVs is one way they could communicate. These types of pheromones are not based on chemicals, but rather on the strength of electrical fields. In a computer-based (constructive) simulation, a UAV swarm using digital pheromones significantly outperformed the non-swarm case.

1.8 PUTTING IT ALL TOGETHER

Although some progress has been made – there are UMVs operating in various areas of the world today – no integrated theory of human-automation integration has surfaced as of this writing. Perhaps this should not be a surprise. The integration of humans and automation is what is called a “wicked” problem, one not answered by simple solutions. However, the fact that UMVs are operational gives us hope that the problem is not intractable. In addition, ideas expressed in the following chapters offer a great potential for solving this “wicked” problem.

INTRODUCTION



Chapter 2 – MILITARY RELEVANCE

Chapter Lead: R. Taylor

Contributors: G. Carver, P. Kennett, P. Stensson, R. Taylor

2.1 PART I – MILITARY RELEVANCE OF HUMAN FACTORS OF UMV SYSTEMS

2.1.1 Introduction

“Now it is clear the military does not have enough unmanned vehicles. We are entering an era in which unmanned vehicles of all kind will take on greater importance – in space, on land, in the air and at sea.”

President George W Bush, address to the Citadel, December 2001.

Unmanned Military Vehicles (UMVs) are enablers of military capability with clear endorsement at the highest level. Many NATO Nations have active programmes to develop and integrate UMV systems into the front line military force mix. UMVs are most commonly characterised as dealing well with 3D tasks – dull, dirty and dangerous. They are used extensively in intelligence, surveillance and reconnaissance (ISR) roles, affording persistence in the provision of critical information, without risking lives. Increasingly, they are being considered for combat and support roles. Modern warfare needs military capability to respond to the threat of conventional hostile force and to the challenges of asymmetric conflicts, where political and military success relies on effects-based targeting and operations. In the age of Network Centric Warfare (NCW), ISR information supplied by UMV systems can be a key combat multiplier in the hands of a commander [1]. Automation technology and computer-based information processing are increasingly important for balancing affordability, capability and achievability with increasing pressures on scarce, skilled human resources. Important questions remain about what realistic effects can be expected to be achieved by UMVs in the uncertain, ambiguous and non-linear battle-space of the future, including how international law will interpret robotic warfare in the future [2,3]. However, the main consideration of this report is not so much the military relevance of UMVs, since this seems mostly self evident. Rather, the key issue is to establish why *human factors* (HF) are important military relevant issues with “unmanned” technologies. Since UMV technologies are expected to actually reduce human involvement in some tasks, it is not self evident why HF issues should warrant raised attention. Thus, the reasons for raising HF concerns are in need of review. In this report, when referencing UMVs, the term “uninhabited” will be substituted for “unmanned” where appropriate, in recognition of the role of both women and men equally in serving our armed forces.

2.1.1.1 References

- [1] Curran, M. (2005). UAVs: A Critical Multiplier for Current and Future Forces. RUSI Defence Systems, Summer 2005. pp. 64-66. London, Royal United Services Institute.
- [2] Burrige, B. (2005). Post-modern warfighting with unmanned vehicle systems: Esoteric chimera or essential capability. RUSI Journal, October 2005, 150 (5). London, Royal United Services Institute.
- [3] Kennett, P.D. (2005). Autonomous Killing Machines – The Technical, Legal and Moral Implications. Defence Research Paper, Advanced Command and Staff Course No 8, September 04 – July 05, Joint Services Command and Staff College, March 2005.

MILITARY RELEVANCE

2.1.2 Human Factors

2.1.2.1 User Requirements

UMVs are valued variously as force-multipliers, as augmenters of the force, and as adding a new component to the military force mix – but ultimately, UMVs are tools for human use. Human effectiveness is the key to all military capability. UMVs are enablers of human effectiveness and military capability. Human involvement in UMV systems is of paramount importance. HF issues need to be in the sharpest focus to mitigate the unacceptable risks of de-humanisation of decision-making in warfare.

Air Chief Marshall Sir Brian Burridge believes that in order to appreciate the capability of UAVs, we need to appreciate their limitations and benefits, but that understanding of the human dimension is the most important of all – knowing how to use them, task them and to integrate them [1]. Use of UMVs is generally justified on grounds of capability, affordability and safety. UMVs can make certain tasks safer by reducing human involvement and risk to life, allowing the possibility of human resources being re-deployed more efficiently and effectively. This produces complex changes in the balance and priority of HF issues for UMV systems. Paradoxically, for many aspects of UMV system engineering and operation, the proper consideration of HF has even greater military relevance. Human involvement remains essential throughout the UMV system life cycle, including UMV operations. As a discipline, HF provides the tools for understanding and ensuring the correct human involvement in the UMV system life cycle. Obviously, UMV habitability is not a concern. However, vehicle maintenance is still needed. Vehicle control and safety becomes a complex issue, especially when mixing UMVs with manned vehicles and “dismounted” forces. Increasing levels of UMV autonomy are expected to reduce the need for human intervention in operations. However, UMVs are not a substitute for human involvement in the battle-space. Crucially, human control of UMVs is axiomatic for military relevance (for a detailed argument for the axiomatic requirement for human control, see Chapter 2, Part II). Consideration of the technological viability of autonomous systems, and the legal constraints, suggests that a “human-in-the-loop” system will be the most valuable and therefore the most likely mode of operation to provide the required supervision and discrimination [2].

2.1.2.1.1 *Battle-Space Connectivity*

In warfare, the problems and outcomes are complex, dynamic, uncertain and risky, and the application of critical judgement and decision making is crucial to successful conflict resolution. Context sensitivity is important for assessing the quality of military decision making [3]. Humans encode context naturally and handle decision making adaptively with incomplete, partial and uncertain information. This provides decision making capability not easily matched by artificial intelligence (AI) in computers. However, to exercise good military judgement, humans need to feel the texture and “granularity of the battle-space” [1]. UMV operators removed from the immediate context of use, risk losing “emotional connectivity of the battle-space”, operator context sensitivity and system adaptiveness. For autonomous UMV operations, the detailed level of operator supervision required is likely to be dependent on the individual mission context and the Rules of Engagement (RoE). This can be difficult or impossible to anticipate fully in advance. As a minimum, the operator needs to be able to discriminate between what is a valid military target and what is not.

2.1.2.1.2 *Human in Control*

Technological limitations, legal and moral constraints, and most effective human involvement, suggest that some form of human-in-the-loop control always will be required. Currently, with manned vehicles, the human operator provides the flexibility to adapt to constraints on functioning arising from system design, creates on-line tolerance of variability and uncertainty in the external environment, and offers adaptation to changing

dynamic mission context. The requirements for human-in-the-loop control of UMV operations, either remote or reach-back, can be considered as occurring at a number of levels depending on the level of automation, e.g., tasks, functions, tactical and strategic mission goals. Classes of control can be characterised as either manual, semi-automatic, and fully autonomous, with and without human supervisory control. Generally, automation best serves human purposes by enabling higher levels of human control, i.e., automate routine 3D tasks and support human supervisory control at tactical and strategic levels. The challenge is to determine the precise level of supervision required, and to identify the detailed user requirements and HF engineering solutions, for efficient and effective supervisory control.

In highly autonomous operations, communications permitting, humans can retain high level supervisory control through setting and monitoring of tasks and goals, and through authorisation of safety critical actions and use of lethal force. However, experience of automation supervision elsewhere, in particular in the process control industry and with flight deck automation has shown that reliable and robust human supervisory control is inherently difficult to achieve. Dependence on human supervisory control is risky for safety critical events and tasks. Limitations on cognition (perception, learning, memory and reasoning) mean that it is inherently difficult for humans to perform supervisory control in a consistent and reliable manner, particularly during sustained operations requiring vigilance and unpredictably intermittent high levels of attentional engagement. Ultimately, there is a risk that the over-use of automation may reduce human authority, responsibility and competency. Crucially, over-use of automation risks de-skilling the user in the important cognitive domain, reducing the essential human capability for exercising critical judgement and decision making in the appropriate use of lethal force. Finally, over-use of automation implies the risk that the human supervisor is placed 'out-of-the loop' so that he lacks actual process state knowledge (so-called peripherisation effect).

Supervisory control requires robust and reliable communications with the battle-space. The realities of military communications present a real dilemma for the supervisory control paradigm. In practice, communications technology limitations (e.g., line-of-sight and bandwidth restrictions, information quality, latency) and communications breakdown (e.g., hostile interference, electronic countermeasures) can limit feedback on mission performance and prevent real-time mission intervention during remote control operations. This may necessitate detailed mission planning, including contingencies for restricted autonomous operations when human supervision and authorisation is denied.

2.1.2.1.3 Authority and Responsibility

Human involvement is required in military operations to direct and plan the use of military capability, and to ensure lawfully correct use of lethal force. This is achieved through the application of human command authority, responsibility and accountability, and competency. With autonomous UMVs, some of that responsibility is delegated to increasingly competent computer controlled machines, but the authority and accountability for the delegation ultimately remains with humans. Ensuring the correct human involvement in UMV operations provides issues for Command and Control (C2), concept of operations (CONOPS), ROE and for the specific information display and control requirements in the context of use, i.e., ISR, combat, or support roles. For military relevance, UMV autonomy concepts must be integrated with the C2 requirements of both national and international C2 infrastructures (joint and coalition operations). C2 is rooted in human authority, responsibility and accountability, will, leadership and competency in judgement and decision making [4,5]. The potential for fully autonomous UMV operations presents significant challenges for concepts and principles of military C2. UMV control requirements need to be integrated with C2 frameworks and architectures (information flows, decision nodes, dynamic interactions), chains of command and CONOPS. This is to ensure leadership and the correct delegation of human authority, responsibility and accountability, and the necessary dynamic human interactions, with appropriate levels of trust.

MILITARY RELEVANCE

2.1.2.1.4 *Comprehension of Meaning*

UMVs are used extensively to gather information in ISR roles for human interpretation. ISR information is inherently incomplete and uncertain. Fundamentally, computer-based information processing systems are limited in that they can not comprehend the meaning of information in human cognitive terms, e.g., apply knowledge, understand, feel truth, appreciate implications, judge consequences. Critical military judgement is needed to interpret the meaning of ISR information. Crucially, UMVs can not appreciate the effects of use of lethal force. An “emotional connectivity” is needed to appreciate the “moral value of killing and the value of human life” [2]. Critical military judgement is needed for decisions on use of lethal force. Failure to ensure proper human involvement risks rendering UMVs as unusable tools for military purposes.

2.1.2.2 **Integration of Human and Automation Requirements**

As a speciality, HF is traditionally concerned with the study of the man-machine interface. This also includes consideration of the equipment, the physical environment, the tasks and the individuals who do the work. Humans are involved throughout the UMV life cycle, from conceptualisation, specification, design and development, through command, control, operation and maintenance, to decommissioning. The term Human Systems Integration (HSI) is increasingly used in NATO nations to cover the broad scope of human considerations needed from a human-centred approach to systems engineering (or in a system-of-systems approach). The following definition of HSI has been agreed by NATO NSA Aircrew Integration Panel for addition to AAP-45 (NATO Glossary of Aircraft – Aircrew Integration (AI) Specialist Terminology and Abbreviations): “*The technical process of integrating the interdependent elements of Human Factors Engineering, Manpower, Personnel, Training, System Safety, Health Hazards, Survivability, and Habitability into the system acquisition process to ensure the safe and effective operability and supportability with minimised Life Cycle Cost (LCC)*”. UMVs change the challenges of system safety, health hazards, survivability and habitability, reducing risks compared with manned vehicles, particularly for remote “reach-back” operations. Otherwise the HSI domains of HF Engineering, Manpower, Personnel, Training, remain as ever highly relevant for the UMV system life cycle. Notwithstanding, achieving the correct human–automation integration is a key HSI challenge for UMVs, with significant implications for HF Engineering, Manpower, Personnel and Training.

2.1.2.2.1 *Manpower*

Generally, UMVs are expected to augment the force and to create potential savings in human resources, manning levels and training. However, Air Chief Marshall Sir Brian Burridge, Commander in Chief, Strike, of the Royal Air Force (RAF) describes how the current manpower burden of remotely piloted operations is significant, and should not be underestimated [1]. The Air Chief Marshall reports that as part of the Predator Task Force at Nellis Air Force Base, the RAF mans a single Predator A Orbit in support of the coalition intelligence, surveillance and reconnaissance effort. This RAF unit, 115 Flight, totals 44 RAF personnel. He explains that a Predator A can orbit for 20 hours and requires 2 crew who operate for 8 hours each, totalling 6 crew for a single Predator. In addition, the operation involves analysts, data link managers, engineers in the deployed location, and the crews required to launch and to recover the UAV in theatre. This corresponds to a considerable manpower intensive effort, in stark contrast with the current aspiration of UAVs to reduce the manpower burden. In the future, UMVs may be expected to operate with increased levels of autonomy, with concomitant reductions in human involvement in platform control. Estimates of savings require comparisons with manned aircraft operations providing the same level of persistence – but on the evidence from Predator A operations, we should be careful not to underestimate the human resources requirements of UMV operations.

Esler [6] describes how the Global Hawk High Altitude Endurance UAV system, with relatively higher levels of autonomous functioning compared with Predator, has ground control facilities comprising two elements, the Launch and Recovery Element (LRE) and the Mission Control Element (MCE). The LRE accommodates two persons and is responsible for pre-flight and post-flight ground operations and the takeoff and landing phases of flight. The MCE accommodates four persons and is responsible for the mission portion of the flight, when the vehicle is at cruise altitude.

Currently, it is a priority in many NATO Nations UAV research programmes to reduce the manpower burden by reducing the ratio of operators to vehicles for flight and mission control. A common aim is to increase operator effectiveness by enabling a single operator to control multiple UAVs simultaneously (typically up to four) by introducing increased levels of automation, operator decision aiding and advanced human-computer interfaces (HCI).

2.1.2.2.2 Personnel and Training

Air Chief Marshall Sir Brian Burridge considers that softer human issues associated with operator selection and training need to be addressed urgently, ahead of some of the technological issues [1]. Predator is remotely operated by a pilot and a sensor operator. Other UAVs use a computer operator. The Air Chief Marshall expresses concern that without proper training, operators “could be faced with the very real possibility of unwrapping one of these systems for the first time on operations”. Integration and interaction with civilian airspace constraints is a key training issue. He emphasises the importance of previous military experience gained in operations. The experience of operating manned platforms enables them to interact with other units and to operate safely within airspace. He notes that they understand the needs of other units through this shared connection. Solutions may need to be found in the selection of personnel with appropriate operational experience, and in creating an appropriate work context for proper operator task engagement through a combination of HF engineering, HCI and training in RoE and effects appreciation.

In the future, the possibility of increasingly autonomous UMVs can be expected to place greater cognitive demands on the operator, with little or no manual control required. Basic military skills and knowledge will continue to be important, such as airmanship and seamanship. The role of psychomotor abilities will become diminished. Performance of tasks that are likely to be required include:

- Managing and controlling multiple UMV missions;
- Co-ordination and de-confliction of multiple UMV assets;
- Interpreting and integrating command strategic intent, RoE and mission control requirements;
- Recognizing and dealing with degraded system functionality;
- Regaining SA after loss of UMV data links;
- Interpreting displays containing multiple UMV perspectives;
- Shift of system control to other team members or control stations; and
- Team-working and interpersonal interaction.

The emphasis will be on the UMV operator as a mission manager, on multi-task management and performance, on judgement and decision-making skills, and on the cognitive ability to integrate and interpret dynamic, complex data, in order to make rapid and effective decisions. For a detailed discussion of manpower, skills and training requirements, see Chapter 4.

2.1.2.2.3 *HF Engineering*

From a system-of-systems point of view, the term “unmanned” is potentially misleading. It is most certainly inappropriate from an HF engineering perspective. It suggests an absence, or a reduction, in human involvement, and consequently a lack of, or a lessening, in human system issues. This is particularly unfortunate since the opposite is probably nearer the truth. UMVs remove humans from the vehicle (or platform) and the hazardous operating environment. However, UMVs do not remove humans from the system of use. At the present time, with human-in-the-loop control, advances in autonomous vehicle technologies are worthless without an effective and efficient operator remote control/display interface [7].

Generally, separating operators from the context of use risks disconnection from the battle-space, reduced SA, and creates difficulty in decision making and in maintaining the level of control and feedback on the effects of use. Rather than reducing the human system issues, increasing remoteness may risk reducing the operator’s capability to provide effective task engagement, situation appreciation and timely interventions. Increased levels of autonomy may reduce some of the human-in-the-loop workload, but autonomy risks the effects of disconnection identified above. Research is needed both on AI techniques for autonomy and on HF of supervisory control. For a detailed discussion of relevant AI techniques, see Chapter 5. The risk of disconnection raises the importance of HF engineering for enabling supervisory control and for exploiting the potential mitigations afforded by advanced HCI design, augmented cognition technologies, SA tools and operator decision support aids. HCI style guide information is available for interoperability between UAV Control Stations (UCS) in NATO STANAG 4586 [8]. HCI is a rapidly advancing field and research is needed to provide properly validated advanced HCI solutions for future improved UCS. For a detailed discussion of advanced UMV operator interfaces control/display requirements, see Chapter 6.

It has been suggested that UMVs may shift the balance of responsibility and accountability for UMV behaviours and effects from users’ decisions during systems operation towards engineers’ decisions during system design. The development of this argument could depend on technological developments affecting the future possibility of machines that never make mistakes, the levels of automation employed, and the methods of supervisory control of operations and effects. International humanitarian law on military use of lethal force in conflict seems likely to keep responsibility and accountability firmly with the user/commander. So, with increasing levels of autonomy, the need for system transparency and SA could grow. User involvement in systems requirement specification will become increasingly important to ensure that critical military judgement can be properly exercised in the context of use. This could necessitate real time user/commander control of the level of automation (i.e., adjustable, variable levels of automation), in addition to supervisory control of the specific UMV operations and effects.

2.1.2.2.4 *Human-Computer Decision Partnership*

Reising [9] describes how in the future, rather than coping with unreliable human supervisory control, or simply removing the operator from the control loop entirely, the paradigm for operator control will need to progress to one based on human-computer co-operation, as implemented in advanced pilot assistance systems. Reising predicts that future UMVs will contain associate systems that will enable the UMV operator and the associate to form a team of two crewmembers – one human and one electronic. Onken [10] calls this partnership *cognitive co-operation*. Ensuring the success of this necessary partnership presents significant challenges for HF of UMV systems. Research has shown how real-time HF engineering of variable levels of automation or adjustable levels of autonomy are important for controlling multiple autonomous UMVs, and provide the key to developing an adaptive human-computer decision partnership [11,12,13]. Alternative theoretical frameworks for UMV systems are discussed in Chapter 3. Levels of automation are discussed in detail in Chapter 7.

Ideally, a flexible approach is needed that allows a variable level of human intervention and autonomy, with the need for “drill-down” judged in real-time. For efficient and effective mission supervision and discrimination, the operator/supervisor needs to be able to bring added value to the understanding of the situation [14]. To add value, he/she will need to be able to use knowledge (e.g., RoE, situation awareness, tactics) and to take into account additional contextual decision information not available to the UVM information processing system. Otherwise, the level of supervision may be uncritical and lack any real operator decision input, with the resultant legal implications. One example to avoid would be authorising target prosecution for autonomous UVMs based only on pre-set automatic target recognition (ATR) criteria without independent operator verification of the target context RoE. To mitigate this, the C2 system and UCS need to provide a rich operating picture for mission assessment and appropriate mission performance critiquing tools.

2.1.2.3 References

- [1] Burrige, B. (2005). Post-modern warfighting with unmanned vehicle systems: Esoteric chimera or essential capability. *RUSI Journal*, October 2005, 150 (5). London, Royal United Services Institute.
- [2] Kennett, P.D. (2005). Autonomous Killing Machines – The Technical, Legal and Moral Implications. Defence Research Paper, Advanced Command and Staff Course No 8, September 04 – July 05, Joint Services Command and Staff College, March 2005.
- [3] Bolia, R.S., Nelson, W.T., Vidulich, M.A. and Taylor, R.M. (2004). From chess to chancellorsville: Measuring decision quality in military commanders. In: D.A. Vincenzi, Mouloua, M. and Hancock, P.A. (Eds), *Human Performance, Situation Awareness and Automation: Current Research and Trends*, HPSAA II, Volume I. pp. 269-273. Mahwah, NJ: Lawrence Erlbaum.
- [4] Pigeau, R.A. and McCann, C. (2000). Re-defining Command and Control. In: C. McCann and R.A. Pigeau (Eds.), *The Human in Command: Exploring the Modern Military Experience* (pp. 163-184). New York: Kluwer Academic/Plenum Publishers.
- [5] Pigeau, R.A. and McCann, C. (2002). Re-conceptualising Command and Control. *Canadian Military Journal*, 3(1), 53-63.
- [6] Esker, M. (2004). Projection of Workload in Multiple UAV Control. In: *Uninhabited Military Vehicles (UMVs) – Human Factors of Augmenting the Force*. RTO-MP-111, RWS-010-OKN2. Proceedings of the NATO RTO Human Factors and Medical Panel Workshop held in Leiden, The Netherlands, 10-13 June 2003. NATO RTO: Neuilly-sur-Seine Cedex. March 2004.
- [7] Taylor, R.M. (2003). Capability, Cognition and Autonomy. In: *The Role of Humans in Intelligent and Automated Systems*, MP-088, Keynote Address KN-03. Proceedings of the NATO RTO Human Factors and Medicine Panel Symposium, HFM-084/SY-009, held in Warsaw, Poland, 7-9 October 2002. NATO RTO: Neuilly-sur-Seine Cedex.
- [8] NATO, (2001). STANAG 4586 Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability, NATO Military Agency for Standardisation, Draft Version 2.4 September 2001.
- [9] Reising, J. (2003). Uninhabited Military Vehicles: What is the Role of the Operators? In: *The Role of Humans in Intelligent and Automated Systems*, MP-088, Keynote Address KN-04. Proceedings of the NATO RTO Human Factors and Medicine Panel Symposium, HFM-084/SY-009, held in Warsaw, Poland, 7-9 October 2002. NATO RTO: Neuilly-sur-Seine Cedex.

- [10] Onken, R. (2003). Cognitive Co-operation for the Sake of Human-Machine Team Effectiveness. In: The Role of Humans in Intelligent and Automated Systems, MP-088, Keynote Address KN-05. Proceedings of the NATO RTO Human Factors and Medicine Panel Symposium, HFM-084/SY-009, held in Warsaw, Poland, 7-9 October 2002. NATO RTO: Neuilly-sur-Seine Cedex.
- [11] White, A.D. (2002). The human-machine partnership in UCAV operations. In: Proceedings of 17th Bristol UAV Systems Conference, 10-13 April 2002.
- [12] Ruff, H.A., Calhoun, G.L., Draper, M.H., Fontejon, J.V. and Guilfoos, B.J. (2004). In: D.A. Vincenzi, Mouloua, M. and Hancock, P.A. (Eds), Human Performance, Situation Awareness and Automation: Current Research and Trends, HPSAA II, Volume II, pp. 218-222. Mahwah, NJ: Lawrence Erlbaum.
- [13] Frampton, R. (2005). UAV Autonomy. Distillation, The Dstl Science Journal, Issue 9, pp. 16-19.
- [14] Cottrell, R.J., Dixon, D.G., Hope, T. and Taylor, R.M. (2005). Operator in the loop? Adaptive Decision Support for Military Air Missions. In: Proceedings of the 1st International Conference on Augmented Cognition, Las Vegas NV, 25-27 July 2005. New Jersey: Erlbaum.

2.1.3 Operational Benefits of UMVs

Interoperability within the force mix is a key challenge for UMVs and HF. Commodore Lambert, UK Director of Equipment Capability (Underwater Battle-space) has characterised the battle-space of today as encompassing air, land and sea domains, requiring sensor coverage and connectivity across all boundaries [1]. In this battle-space, Commodore Lambert has identified several operational advantages in military missions derived from employing UMVs in airborne, ground and underwater systems:

- Minimise or eliminate risk to personnel and expensive platforms through autonomy.
- Access, under all-conditions, to denied or unsafe areas of operations.
- Force multiplication through the ability to operate independently for extended periods, enabling manned platforms to extend their reach and focus on more complex tasks.
- Automated reconnaissance, surveillance, target acquisition, target designation, tactical oceanography, battle damage assessment, etc., through the use of miniaturised, low energy sensors/payloads.
- Secure network enabled warfare via data relay and connectivity at extended ranges between multiple vehicles.
- Mission flexibility through their ability to be deployed from a variety of host platforms.

Of the three main classes of UMVs – airborne, ground and underwater systems – uninhabited air vehicles (UAVs) and to a lesser extent, uninhabited underwater vehicles (UUVs) have attracted the wider operational interest. UAVs have probably resulted in the most significant technical activity from a human factors perspective. The following sections reflect this balance of military interest, HF issues and research activity.

2.1.3.1 Uninhabited Ground Vehicles

Uninhabited ground vehicles (UGVs) were first used by the German Army in World War II for tasks such as mine field breaching (e.g., Goliath, Borgward IV). Early UGVs have been particularly successful in support of space operations, such as the Lunar and Mars rover vehicles. The first such vehicle was the Russian Lunakhod 1 which was tele-operated on the moon in the 1970s for 11 days over a distance of 10 km. Currently,

the majority of UGVs are tele-operated line-of-sight systems, with research directed at the development of autonomous unmanned/robotic technology. Strong [2] summarises the potential use of UGVs as including the following roles:

- Mine detection and neutralisation;
- Explosive ordnance clearance and disposal;
- Reconnaissance, surveillance and target acquisition;
- Operations in contaminated areas and contamination assessment (e.g., detection and analysis of chemical, nuclear and biological assets);
- Urban warfare operations in confined spaces;
- Fire fighting;
- Logistics (e.g., delivery to the battlefield of munitions, fuel, parts, food and water);
- Casualty recovery;
- Security and patrol;
- Deployment of weapons or obscurants;
- Deployment as a mobile communications link;
- Deployment as a mobile power supply; and
- Deployment as a decoy target.

Current UGVs have important military roles for reconnaissance and surveillance in support of urban operations, particularly for working in confined, restricted and dangerous environments, such as fire-fighting (e.g., Carlos), breaching (e.g., Caterpillar D7), searching underground in caves, culverts, drains and man holes and searching collapsed buildings, i.e., areas not subject to aerial observation (e.g. PackBots, Man Portable Robotic System). Generally, for military purposes, UGVs experience major challenges to mobility and manoeuvrability due to sensing and avoidance difficulties with unexpected ground obstacles and crevices, and due to terrains (rugged going, gradients, instability, terrain, grip and ground clearance; building sites and interiors; smooth surfaces; cluttered environments; low tide, streams, puddles, mud). Research has shown that failure rates in urban terrain are relatively high with a mean-time between failures on average of between 6 – 20 hours. Because of the relatively restricted nature of UGV tasks, they are relatively unsophisticated in terms of requirements for levels of automation and autonomous functioning. UGVs are mostly operated by remote control, requiring robust, compact and portable operator control stations, with relatively simple control and display interfaces.

Remotely controlled UGVs have a significant current role as tools for detecting hazardous and dangerous materials (chemical, biological, radiation, nuclear – CBRN), and in particular for counter-mine, Explosive Ordnance Devices (EOD) and Improvised Explosive Devices (IED) tasks, e.g., RONS – Remote Ordnance Neutralisation System; ARTS-All purpose Robotic Transportation System; M60 Panther (Common Robotic System), a tele-operated turret-less M1 tank equipped with rollers for mine clearance; Mini Flail for anti-personnel mines and booby traps; Wheelbarrow tele-operated tracked robotic bomb disposal vehicle; Cyclops, and Buckeye Miniature Remotely Operated Vehicle (MROV) for work in urban areas and confined spaces, such as aircraft, buses and trains; Talon, a remotely operated vehicle-based telescopic manipulator, acts as both a reconnaissance vehicle and a weapon and camera platform. The current version of Talon is a semi-autonomous unmanned vehicle capable of firing rifles, machine guns, grenade launchers and rockets.

MILITARY RELEVANCE

Control of UGVs for EOD/IED operations involves the following HF challenges:

- Systems operations difficulties – power supply management, ambient lighting problems, visual issues, control feedback.
- System performance issues – lag and gain in control response critical for EOD/IED work, stopping distance, proportional gain controls, mode types, simultaneous control of multiple parameters.
- Operating from moving platforms – motion sickness, orientation.

In addition, the EOD/IED operational environment involves complex problem solving and high levels of operator situational awareness. This requires high levels of operator and team skills and experience. Training of EOD/IED operators is an important area for HF work. This summary of EOD/IED HF requirements is based on the UGV briefing by Paul Burns, SOE Academy and Nicki Heath, Symbiotics, provided to HFM-018 at the meeting in Bath, UK on 24 May 2005.

UGVs are currently used for payload delivery (e.g., R-Gator, Military Robotic Gator), such as fire brigade, medical supplies, hostage scenarios and electronic counter measures (ECM) equipments. Digney [3] provides a review of research at DRDC-Suffield on UGVs including the following:

- Unmanned Scout Vehicle – Tele-operated, for reconnaissance operations;
- Caterpillar D7 – Both telematic and on-board human operator, for earth working; and
- Improved Landmine Detection Programme (ILDLP) – Telematic control for landmine detection.

Digney summarises the military benefits and issues of UGVs as follows:

- Removal of soldiers from hazardous and hostile environments.
- Robot must win – whatever telematic, shared control or autonomous system is fielded, the robot must prevail in competitive conflict.
- Hiding complexity from operator control – provide autonomous control of low level functions, while human controllers supply high level and intuitive directives.
- Amplified use of manpower – field more vehicles per human controller, and deploy freed personnel to other vital roles.
- Persistent attention – use shared control and persistent search for detection of scene changes and enlist human assistance in change classification, to mitigate fatigue and inattentiveness.
- Lethal force control – automatic control of lethal force is not permitted by current ethical considerations. Whenever lethal force is to be applied from an UMV, a human operator must be in direct control.
- Life critical operations – infra-red image classification on the IDLP mine detection vehicle is currently done by a human because automatic classification performance risks machine classification error and endangers human lives.
- Sacrificial vehicles – unmanned vehicles losses are more acceptable.
- Communications silence and jamming – Urban areas exacerbate problems with communications links assurance, jamming of communications is common, communications give positions and intent away, and should be kept to a minimum and performed through undetectable means.

- Acceptable path to higher autonomy – use incremental route levels of autonomy, supported by incremental verification, a demonstrable safe path, with progress and reliability observed by the operator.

Future UGVs are envisioned for more complex and hazardous tasks, such as casualty evacuation (REV-Robot Evacuation Vehicle, REX-Robotic Extraction Vehicle), with more challenging technical requirements, complex safety issues, and potentially high levels of automation. Future UGVs are planned with improved capability for remote-controlled, semi-autonomous and autonomous operation and improved mobility, flexibility and multi-functionality. Enabling technologies include ground positioning systems, autonomous navigation, automatic collision avoidance, perception and navigation sensors, intricate and precise positioning, and artificial intelligence techniques (e.g., hierarchical learning, adaptive control, neural networks). The US Army's planned Future Combat System (FCS) is largely built on UMV concepts (manned vehicles plus UAVs, unattended munitions and UGVs). FCS UGVs comprise the Armed Robotic Vehicle (ARV) with assault and RSTA (Reconnaissance, Surveillance, and Target Acquisition) variants, and the Multi-purpose Utility/Logistics Equipment (MULE) for countermine and transport.

Looking further to the future, the US Joint Forces Command's Project Alpha includes "Unmanned Effects: Taking Humans Out of the Loop". This seeks to explore the idea of that autonomous, networked and integrated robots may be the dominant fighting force by the year 2025 (<http://www.jfcom.mil/newslink/storyarchive/2003/pa072903.htm> accessed 12/12/2005). In 2003, DARPA's "Centibots" project on distributed robotics looked at co-ordinated deployment of groups of 25 – 50 robots in advanced surveillance teams for urban missions, including area surveying, sharing a distributed map and intruder detection (<http://www.ai.sri.com/centibots> accessed 20/11/2005). Several advanced research programmes are using biomimetics, the engineering of a process or system that mimics biology, to investigate behaviours in robots that emulate animals such as self-healing and swarming [2].

2.1.3.2 Uninhabited Underwater Vehicles

Uninhabited underwater vehicles (UUVs) have been deployed by NATO Nations in a variety of civilian and military roles. Both US and UK have active research and development programmes. In the military underwater domain, more than others, research has been characterised by a desire for a direct route to behaviourally simple, but fully autonomous, UUVs. This seems mostly due to the military importance of the littoral zone with very shallow water (VSW) and surf-zone (SZ) operations, and the associated problems of difficult underwater acoustic communications (AComms).

Carver [4] has identified a variety of roles for UUVs in the underwater battle-space derived from operational analysis, surveys of likely users and initial concept of operations studies:

- Mine Countermeasures (MCM);
- Environmental Data Gathering (EDG);
- Rapid Environmental Assessment (REA);
- Above and Below Water Intelligence Gathering;
- Anti Submarine Warfare (ASW) – Trainer;
- Expendable Sensor Deployment;
- Mobile Signature Range;

MILITARY RELEVANCE

- ASW Bi-Static Sonar Operations; and
- ASW Track and Trail.

Commercially available Remotely Operated Vehicles (ROVs) are in relative abundance for deepwater operations. Underwater ROVs tend to be tethered to a mother ship via an umbilical cord, supplying power and command and communications links. There is considerable experience using underwater ROVs in the oil industry for offshore support. Specific examples include the Maridan 600 ROV UUV from Denmark, and the Hugin ROV UUV out of Norway. In addition, UUVs have been used in varied environments for scientific work. Academic ROVs include the Woods Hole Oceanographic Institute's REMUS (Remote Environmental Monitoring UnitS), Florida Atlantic University's Morpheus, Massachusetts Institute of Technology's Odyssey and Cetus II, and Southampton Oceanography Centre's AutoSub UUV. In the UK, Tiltman [5] reports that the combined experience of industry and academia is currently being used to reduce the risk to UUV procurement for the next 10 years under the UK MOD Battlespace Access UUV (BAUUV) programme, 2003 – 2006.

Tiltman [5] describes how the UK MARLIN 1995 – 2003 research and development programme was based on torpedo technology from SPEARFISH and MK24's. MARLIN was designed for submarine launch and recovery, with a unique top speed of 15 kts. Recovery proved particularly difficult and requirements for submarine operations have subsequently waned. He reports that the Royal Navy currently has two derivative REMUS UUVs in active service, surveying areas in and around ports, harbours, ship lanes and landing areas. The US Navy is developing LMRS (Long Term Mine Reconnaissance System), a mine hunting UUV. These free swimming UUVs tend to be very small, of limited endurance, with a single specific task, such as inspection of underwater objects. Tiltman reports that joint US/UK GAMBIT programme is developing mine-warfare UUV sensors. GAMBIT uses a 21" UUV built by Bluefin Robotics to investigate Synthetic Aperture Sonar (SAS), mission autonomy and navigation systems. He believes that SAS holds the possibility of allowing a UUV to survey a boat lane in one sweep at 4 kts. This will significantly change mine warfare tactics, affect the whole amphibious operation, and significantly reduce the risk to military personnel.

Posey [6] argues that MCM is a key role for UUVs, e.g., RAUVER, REMUS. The sea mine remains a powerful and cost effective asymmetric threat of significant concern to the maritime forces. Posey believes that current dedicated MCM capabilities will not satisfy the requirements of the future battlespace. He reports that this is because current MCM capabilities are limited by lengthy timelines for surface assets to arrive in theatre, inadequate integration of assets, minimal reconnaissance means, and operational pauses created by the slow, deliberate nature of MCM operations.

Waters and Taylor [7] report that the US Navy envisage the littoral zone to be the most important for UUV operations, from MCM prior to a naval assault, through coastal and channel mapping via sonar, to deploying sonars near enemy naval installations to track asset movement and even kill them with torpedoes. MCM and Explosives Ordnance Disposal are key operational tasks for UUVs in VSW/SZ operations. Blackburn et al. [8] report that a VSW MCM detachment comprises 70 personnel: 40 are in operations, mostly diver qualified, 18 go into the water, 21 service and control dolphins, and 6 will operate UUVs. The dolphins locate the mines using endogenous sonar, then drop pingers to tag locations. For SZ operations, brute force neutralisation is used by laying down a blanket of charges for in-stride breaching.

Blackburn et al. [8] note that the closer the UUV is driven to the beach, the greater the sensing, navigation, communications and control problems become. With ROV, in both VSW/SZ and deep water operations, there is the possibility of increased difficulty of task execution with tele-operated ROV control from a distance. This is particularly problematic if information is changing quickly, or restricted, as it often is in the complex terrestrial environment and near beach underwater environment.

A major factor governing UUV operations is the availability of power. Strong currents and water turbulence can make station keeping difficult to achieve and drain power. Walters and Taylor [7] describe how retaining and managing power is an important UUV task, and a strong candidate for automation. The power source will also have to be wholly internal to the vehicle. This is currently based on batteries, although it is likely that fuel cells will replace these as the technology improves. Even the latter will only yield a useful energy output of about 400Wh per kg, with the potential to (possibly) double this figure within the next 5 years. With current UUVs, such as the USS Manta, requiring up to 50 kW for propulsion alone, plus several kW more for sensor operation (e.g., sonar), the size of the problem of supplying sufficient power to allow the performance of any kind of mission becomes apparent. The addressing of this power management problem, which is usually denoted by HOTEL, boils down to answering the question “can I do the mission and return to my recovery point on my power reserves?” This base-lining of the projected energy consumption for the whole mission, continually updated during the mission, underpins every other assessment and decision made during the mission.

In wider concepts, UUV missions may last for days. Alternatives include large UUVs carrying a variety of sensors and deploying sensor arrays, and smaller vehicles firing torpedoes [4]. This plethora of UUV roles leads to the concept of adopting a modular design, where different operational modules can be fitted, so providing ‘swing roles’ from a baseline vehicle. Carver notes that a common thread emerges. To achieve the desired range and endurance, and to deliver the required capability, UUVs are becoming larger, embodying more autonomy and developing into complex ‘systems of systems.’ As with current UAVs, UUVs will soon fire weapons on command, requiring reliable secure underwater communications systems. Further into the future, the ultimate ‘leap of faith’ will be to permit weapons to be released autonomously.

Looking into the future, iRobot have a DART biomimetic programme for small, autonomous UUVs that emulate the efficiency, acceleration and manoeuvrability of fish. Also, they have proposed ALUV (Ariel Autonomous Legged Underwater Vehicle), a crab-like robot, for mine and obstacle neutralisation. ALUV would secure itself to the mine and await a detonation signal, or deposit an explosive.

2.1.3.3 Uninhabited Air Vehicles

2.1.3.3.1 Benefits of UAVs

In 2004, NATO Industrial Advisory Group (NIAG) Study Group 75 reported an overview of status of UAV technology from a NATO industry perspective [9]. In general, it is believed that the ability of UAVs to perform their missions with autonomous capabilities will be a major step towards achieving flexible, efficient and interoperable military (including combat) operations. Broadly, the advantages of UAVs are believed to include the following:

- Reduced risk to humans;
- Optimised operator performance;
- Reduced training requirements;
- Improved contingency management;
- Reduced data link demands; and
- Increased operational flexibility.

Air Chief Marshall Burridge [10] concisely summarises the strengths and challenges of UAVs as follows:

MILITARY RELEVANCE

Strengths

- Dealing well with 3D tasks – dull, dirty and dangerous;
- Potential response at a number of levels, ranging from resolving tactical firepower problems to providing commander's strategic critical information requirements;
- Ease of re-tasking;
- Increase stand-off ranges for kinetic, and non-kinetic or cognitive attack; and
- Persistence.

Challenges

- Interoperability of systems;
- Vulnerability;
- Limited capacity to address a wide surveillance;
- Insatiable demand for bandwidth; and
- Inability to deal with ambiguity in the same way as manned aircraft.

2.1.3.3.2 *Classes of UAV*

A parallel activity has been conducted under the NATO Systems Concepts and Integration Panel (SCI) Panel, namely NATO SCI-124 Task Group, Architecture for the Integration of Manned and Unmanned Air Vehicles. Close liaison between SCI-124 and HFM-018 was conducted principally by UK, US and GE TG members. This interaction has been particularly beneficial for HFM-018 in identifying a range of UAV assumptions. For the purposes of the present report, basic information on C2 architecture, tasks and classes of UAVs are taken directly from the Final Report of NATO SCI-124 Task Group [11].

Six classes of UAV are identified by SCI-124 with role-specific platform characteristics and control requirements. These are summarised in Table 2-1 below from the SCI-124 Final Report.

Table 2-1: Summary of UAV Classes, Roles and Control

Class	Description	Role	Control
CML-UAV	Like cruise missile Subsonic, reusable Deep penetration, low altitude, terrain following Independent operation or in support of manned strike aircraft	Pre strike recce Post strike recce (BDA) Target identification Target verification Third party target illumination	Automatic: <ul style="list-style-type: none"> • Flying • Pre-programmed: <ul style="list-style-type: none"> • Flight path • Sensor operation UCS: <ul style="list-style-type: none"> • Flight, mission • Update way points • Payload

Class	Description	Role	Control
CAL-UAV (UCAV)	Like combat aircraft Deep penetrating stealthy ground attack Examples: Joint Unmanned Aerial Combat System (J-UCAS) demonstrators: <ul style="list-style-type: none"> Boeing X-45 Northrop Grumman X-47 Pegasus 	Strike SEAD DEAD Recce Surveillance	Automatic: <ul style="list-style-type: none"> Flying Pre-programmed with human-in-the-loop, or autonomous: Target acquisition Target verification Weapon release UCS (+ CAOC, AEWG): <ul style="list-style-type: none"> Flight, mission Update way points Payload
HALE-UAV	High altitude, Long endurance Examples: <ul style="list-style-type: none"> Global Hawk General Atomics Predator B 	Stand off Strategic Over target area Surveillance Recce (IMINT, SIGINT) Target acquisition Stand-off jamming	Automatic: <ul style="list-style-type: none"> Flying Pre-programmed: Flight path Sensor operation UCS: <ul style="list-style-type: none"> Takeoff, landing Flight, mission Update way points Payload
MALE-UAV	Medium altitude – up to 10 km Long endurance, Medium speed Examples: <ul style="list-style-type: none"> Predator Hunter Heron Watchkeeper 	Stand off Tactical Over target area Surveillance Recce (IMINT, SIGINT) Target acquisition Stand-off jamming	Automatic: <ul style="list-style-type: none"> Flying Pre-programmed: Flight path Sensor operation UCS: <ul style="list-style-type: none"> Takeoff, landing Flight, mission Update way points Payload
VTOL-UAV	Future, vertical take-off and landing Forward base operations range (radius) 500 km fast (>300 km/h) low (nap-of-the-earth)	Combat search and rescue (CSAR) Casualty variant (armoured cabin) Escort protection variant: <ul style="list-style-type: none"> Remotely controlled machine guns IR-/TV-cameras 	UCS: <ul style="list-style-type: none"> Monitor and control flight, mission Control/operate escort weapons

MILITARY RELEVANCE

Class	Description	Role	Control
FAL-UAV	Future, like fighter aircraft Air combat Highly agile Supersonic	Air combat, highly reactive against hostile manned fighter aircraft and enemy's UAVs	Automatic: High levels of autonomy (2020): <ul style="list-style-type: none"> • Pre-programmed ingress and egress • Air-target acquisition • Initiation of combat flight manoeuvres • Tactical manoeuvres based on human intelligence • Weapon selection • Weapon release • Fire control UCS (+ CAOC ,AEWC): <ul style="list-style-type: none"> • Flight, mission • Update way points • Monitor autonomous operation • Interrupt weapon release
Mini-UAV	Small portable reusable Takeoff weight < 5 kg Range < 10 km Altitude 500 m Endurance 30 minutes. Example: Dragon Eye	Support for ground forces Beyond visible range (BVR) capability Reconnaissance Target acquisition	UCS: <ul style="list-style-type: none"> • One person operation • Mobile • Laptop • Hand-bag portable

2.1.3.3.3 UAV Control Stations

All the UAV classes identified are operating automatically with pre-programmed flight paths and pre-programmed payload/sensor control. The UAV operators can change the way points and the sensor control functions in the tactical UAV Control Stations (UCS) during the flight. Furthermore, the UAV and payload control can be handed over to the CAOC or other sea-, land- or air-based tactical UCSs at any time during the flight. Autonomy levels define the UAV's level of control and hence the required commands to control it. At present, UAVs need a UCS with an operator. The location of the UCS is critical for future CONOPS. The UCS location could be remote, or located in an accompanying aircraft. The functions of the UCS are summarised by SCI-124 as follows:

- C2 of air vehicle and payload (including weapons);
- Possibly (limited) processing, display and exploitation of sensor data;
- Communications with Air Control Centre (ACC); and
- Dissemination of UAV sensor data to users.

The UCS can be land, sea or air-based. UCS can control many UAVs. One UAV can be controlled (over time) by many UCS both on the ground as airborne, but never at the same time.

Currently, one UCS is needed to operate one UAV. SCI-124 believes that future UAV systems will have the ability to control several vehicles with one UCS. Control of a UAV or payload may be passed from one UCS to another. Control handover and associated operator workload issues will need to be considered in deriving the integration and C2 requirements for a manned and unmanned aircraft mix.

2.1.3.3.4 UAV Autonomous Control Levels

The DoD UAV Roadmap 2002 defines 10 levels of autonomous control (ACL). These provide a quantification of the wide range of UAVs that will affect UCS HF requirements:

- ACL 10 – Fully autonomous swarms;
- ACL 09 – Groups strategic goals;
- ACL 08 – Distributed control;
- ACL 07 – Group tactical goals;
- ACL 06 – Group tactical re-plan;
- ACL 05 – Group coordination;
- ACL 04 – Onboard route re-plan;
- ACL 03 – Adapt to failures and flight conditions;
- ACL 02 – Real time health diagnosis; and
- ACL 01 – Remotely guided.

The Predator UAV is represented as at ACL 2, Global Hawk UAV as at ACL 2.5. ACL 5 should be reached by 2010.

SCI-124 believes that a UAV must respond to commands in a timely way, similar to manned aircraft. This is achieved by the combination of operator intervention and ACL. It is assumed that by definition, at low UAV ACL, there will be much greater operator intervention, and at high ACL, only little operator intervention will be required. Implementation of this vision of increasing delegation of UAV control to automation together with a managed reduction in operator involvement per UAV presents major HF challenges.

Current UAVs have limited sense and avoid capability. SCI-124 have concluded that enhancement of current UAV sense and avoid capability will be essential in order to mix manned and unmanned aircraft in the same package. They note that future UAV systems will require sensors that detect traffic and robust automatic collision avoidance systems that are able to react in a manner similar to a manned aircraft.

2.1.3.3.5 C2/ISR UAVs

Looking to the future requirement for UAVs in the US Army, Curran [12] describes the future core capabilities for command and control (C2), as well as intelligence, surveillance and reconnaissance (ISR). He states that UAVs are becoming increasingly important in enabling ground forces “to *see first, understand first, act first*,

MILITARY RELEVANCE

and then finish *decisively*". He believes that they provide critical information without jeopardising or risking lives. He notes that as range, altitude and loiter time increase UAVs are providing "the eyes" to support line-of-sight and beyond-line-of-sight reconnaissance, fires and over-watch. As a result, Curran describes that this support enables rapid movement, target identification and engagement, and enhanced battle damage assessment, giving commanders greater understanding of the effects of their combat operations. In future, Curran believes that all classes of UAVs will have the following core capabilities:

- Networked systems-of-systems using the Future Combat System (FCS) common operating environment, common computers, software, sensors and battle command communications management.
- Embedded autonomous flight control and navigation, and safe flight protocols.
- Unprecedented reliability, maintainability and operational availability reducing the quantity of logistics support.
- Condition-based maintenance with sophisticated prognosis and diagnosis data networked into the Brigade Combat Team.
- A reusable platform durable against environmental effects.
- Power sources readily available within the BCT and compatible fuel/power cells.
- An anti-tamper capability.
- A means to sense and report a personnel and vehicle presence night and day.
- The ability to report target and platform locations.
- The capability to detect and report location and direction of threat systems acquiring, or targeting, the UAV platform.

2.1.3.3.6 *Combat UAVs*

Of particular significance in looking to the battlefield of the future, the Joint Unmanned Combat System (J-UCAS) is a joint effort between the Defence Advanced Research Projects Agency (DARPA), the US Air Force and the US Navy. Francis and Hirschberg [13] describe how the J-UCAS programme seeks to exploit the potential of a networked system of high performance, weapon-carrying unmanned aircraft with the ability to penetrate and persist deep within the enemy territory. J-UCAS is intended to develop the capability for unmanned aircraft to cooperatively locate and attack an integrated air defence system (IADS) without risking the lives of pilots. Francis and Hirschberg report that the high levels of autonomy planned for J-UCAS are crucial for operating world-wide, independently of degraded communications. Autonomy is needed so that degraded communications, whether caused by sunspots or jamming, must not impair the aircraft functionality or the system's ability to complete missions within the assigned rules of ROE. The example ROE given is the use of force only authorised by the human operator. According to Francis and Hirschberg, the intention is for J-UCAS to move from the current crewing norm involving multiple operators controlling a single UAV, to a new crewing paradigm with multiple aircraft being controlled by a relatively small number of operators. They state that the vision is that this will be achieved with the operators' tasking optimised for workload and mission-critical needs. J-UCAS will collaborate with other J-UCAS aircraft and additional assets to enhance overall SA and improve the speed and precision of geo-location, identification, tracking, and attack and assessment of targets. Operating at the speed and altitude of commercial air traffic, J-UCAS will have a "sense and avoid" capability to be able to operate routinely in the global air traffic management system together with an automated aerial refuelling capability. Collaboration with the UK Ministry of Defence has been established to investigate the military benefits and interoperability issues in future coalition operations through experimentation and distributed real-time simulation.

2.1.3.3.7 NATO Allied Ground Surveillance System

Currently, NATO has a requirement for an Allied Ground Surveillance (AGS) system in support of their activities. AGS is a method to support Peace Keeping and other military operations. It requires a radar system capable of simultaneous Synthetic Aperture Radar (SAR) mode and Moving Target Indicator (MTI) mode. These modes must perform at long stand-off distances and in high resolution. The system must within a large area of interest image any details with the SAR mode; in the MTI mode it must detect, track and classify moving targets. The AGS is primarily designed for military use, but also proves efficient in border control activities.

Five European countries (Germany, France, Italy, Spain, and The Netherlands) have responded to a NATO request and proposed a demonstrator, the Stand Off Surveillance and Target Acquisition System (SOSTAR) [14]. The SOSTAR demonstrator is intended to perform all the required functions of the full scale model, including the simultaneous interleaved operation of SAR and MTI, but has a small antenna size to reduce cost. The system could be used as a basis for an AGS system on UAV's and on small aircraft. The final version of SOSTAR is foreseen to have a scalable antenna and is suitable to be installed on NH-90 helicopter platforms and High Altitude Long Endurance (HALE) UAV's. The system may become available by the end of the decade. The system is set up in such a way that that it can not only fulfil NATO's requirements, but also any upcoming national requirement. Although AGS systems are still in their childhood, the first valuable experiences are there.

2.1.3.3.8 Future Autonomous UAVs

NIAG SG-75 reported the following conclusions regarding the development and operation of autonomous UAVs [10]:

- Operating future autonomous UAV systems within a Network Centric Warfare (NCW) environment will be enable the human to assume the role of system manager, rather than system operator, and that will be advantageous for a variety of missions.
- The development of autonomy for UAV systems is feasible. It will depend not just upon the development of technologies identified in this study, but also upon doctrinal and policy considerations, particularly during operations with combat UAVs.
- Autonomy can be realised incrementally with progressively increasing levels of autonomy. The technologies required to perform UAV autonomous operations have been identified, emphasis being placed on technology solutions that would be possible within 5 – 10 years.
- A number of these technologies were identified to be critical, but are not yet at a Technology Readiness Level (TRL) allowing design and manufacture.
- The level of autonomy will depend upon the capabilities required of an autonomous UAV system, which is a function of the missions the system must perform.
- Technologies duplicating flight crew functions are critical for developing autonomy.
- Development cost can be roughly estimated by the TRL for a technology.
- Cost and risk for developing technologies to meet autonomous capabilities are dependent not only upon the level of maturity of the technology, but also upon mission and system requirements.
- Decision making, modelling, learning, and attack planning have the highest risk/highest cost associated with their development in UAV systems, but they also support the greatest number of autonomous capabilities.

MILITARY RELEVANCE

- Technologies related to status assessment, weapons engagement, prediction, and mission plan update is relatively lower risk and lower cost.
- A number of technologies have been identified which are not uniquely critical, but contribute to different technical solutions for autonomous operations. It is therefore not necessary to develop all of these enabling technologies.
- An autonomous UAV operating within a network centric environment needs to behave with the same reliability and effectiveness as manned elements and ideally, should not require special handling.
- Due to the low TRL of recognising and comprehending natural speech, it is considered improbable that autonomous verbal interaction with civil air traffic control (ATC) can be developed to the level of reliability and integrity demanded by the Authorities. Until ATC interactions will routinely done by data link, autonomous crossing of civil airspace under ATC control is therefore not considered feasible.
- The proposed Technology Demonstration Programmes (TDPs) are an important step in the development of autonomous UAV capacities.
- It is most effective to conduct TDPs that improve the TRL level of technologies from TRL 5 to TRL 6.

2.1.3.4 Summary of UMV Missions, Roles and Tasks

Based on the foregoing, UMV roles and tasks can be broadly distinguished according to vehicle environments (UUV, UGV and UAV) and missions (ISR, Combat and Support Operations). These are summarised in Table 2-2.

Table 2-2: Summary of UMV Missions and Environments

Missions	Uninhabited Ground Vehicles – UGVs	Uninhabited Underwater Vehicles – UUVs	Uninhabited Air Vehicles – UAVs
Intelligence, Surveillance, Reconnaissance	Reconnaissance, surveillance and target acquisition Searching underground in caves, culverts, drains and man holes Searching collapsed buildings	Environmental data gathering Rapid environmental assessment Above and below water intelligence gathering Expendable sensor deployment Deployment of sonars near enemy naval installations ASW Bi-Static sonar operations ASW Track and trail Track asset movement Surveying areas in and around ports, harbours, ship lanes and landing areas Coastal and channel sonar mapping	Pre-strike reconnaissance Post-strike reconnaissance Battle damage assessment Stand-off operations Over target area operations Support for ground forces Beyond visible range (BVR) capability Support line-of-sight and beyond-line-of-sight reconnaissance Stand off ground Surveillance Report target and platform locations Sense and report a personnel and vehicle presence night and day Detect and report location and direction of threat systems acquiring, or targeting, the UAV platform
Combat Operations	Land mine detection and neutralisation Explosive ordnance clearance and disposal (EOD/IED) Urban warfare operations in confined spaces Breaching, earth working Casualty recovery Deployment of weapons or obscurants Firing of rifles, machine guns, grenade launchers and rockets Deployment as a decoy target Hostage scenarios Deployment of electronic counter measures	Mine countermeasures Mine hunting Mine counter measures prior to a naval assault Explosives ordnance disposal Kill enemy assets with torpedoes Mine neutralisation Obstacle neutralisation	Target identification Target verification Third party target illumination Strike Suppression of enemy air defences Destruction of enemy air defences Stand off jamming Stand off target acquisition Air combat, highly reactive against hostile manned fighter aircraft and enemy's UAVs Line-of-sight and beyond-line-of-sight fires and over-watch

MILITARY RELEVANCE

Missions	Uninhabited Ground Vehicles – UGVs	Uninhabited Underwater Vehicles – UUVs	Uninhabited Air Vehicles – UAVs
Support Operations	<p>Operations in contaminated areas and contamination assessment</p> <p>Detection and analysis of chemical, nuclear and biological assets</p> <p>Fire fighting</p> <p>Logistics – delivery to the battlefield of munitions, fuel, parts, food and water</p> <p>Security and patrol</p> <p>Deployment as a mobile communications link</p> <p>Deployment as a mobile power supply</p>	<p>Mobile signature range</p> <p>Anti submarine warfare – Trainer</p>	<p>VTOL combat search and rescue (CSAR)</p> <p>CSAR casualty transport (armoured cabin)</p> <p>CSAR escort protection with remotely controlled machine guns and IR-/TV cameras</p>

2.1.3.5 References

- [1] Lambert, P. (2002). The Role of Unmanned Vehicles and Remote Sensor Systems in the Future Underwater Battlespace. Commodore Paul Lambert Royal Navy, Director of Equipment Capability (Underwater Battlespace), RUSI World Defence Systems, April 2002. London, Royal United Services Institute.
- [2] Strong, G. (2005). Selected Current and Planned Developments in Unmanned Ground Vehicles. Distillation, The Dstl Science Journal, Issue 9, pp. 32-42.
- [3] Digney, B.L. (2002). Human Teaching Learning Machines: Apprentice Systems and Shared Control of Military Vehicles. In: The Role of Humans in Intelligent and Automated Systems, MP-088-04, Paper No 4, pp. 1-30. Proceedings of the NATO RTO Human Factors and Medicine Panel Symposium, HFM-084/SY-009, held in Warsaw, Poland, 7-9 October 2002. NATO RTO: Neuilly-sur-Seine Cedex.
- [4] Carver, G. (2004). Some Human Factors Integration (HFI) Issues Arising from the Operation of Unmanned Underwater Vehicles (UUVs). In: Uninhabited Military Vehicles (UMVs) – Human Factors of Augmenting the Force. RTO-MP-111, RWS-010-OKN1. Proceedings of the NATO RTO Human Factors and Medical Panel Workshop held in Leiden, The Netherlands, 10-13 June 2003. NATO RTO: Neuilly-sur-Seine Cedex. March 2004.
- [5] Tiltman, C. (2005). Review of UUV Work within the Research Programme. Distillation, The Dstl Science Journal, Issue 9, pp. 12-15.
- [6] Posey, C. (2003). Robot Submarines Go To War, Popular Science, April 2003.

- [7] Waters, M. and Taylor, R.M. (2004). A Bayesian Agent Approach to Autonomous Decision Making for an Unattended Cognitive Underwater Vehicle (UCUV). In: Uninhabited Military Vehicles (UMVs) – Human Factors of Augmenting the Force. RTO-MP-111, RWS-010-P4. Proceedings of the NATO RTO Human Factors and Medical Panel Workshop held in Leiden, The Netherlands, 10-13 June 2003. NATO RTO: Neuilly-sur-Seine Cedex. March 2004.
- [8] Blackburn, M.R., Laird, R.T. and Everett, H.R. (2001). Unmanned Ground Vehicles (UGV): Lessons Learned. Technical Report 1869. SPAWAR Systems Centre, SSC San Diego, CA 292152-5001. November 2001.
- [9] NATO, (2004). NATO Industrial Advisory Group, Study Group 75, Pre-Feasibility Study on UAV Autonomous Operations.
- [10] Burrige, B. (2005). Post-modern warfighting with unmanned vehicle systems: Esoteric chimera or essential capability. RUSI Journal, October 2005, 150 (5). London, Royal United Services Institute.
- [11] NATO, (2005). NATO SCI-124 Task Group, Architecture for the Integration of Manned and Unmanned Air Vehicles, Final Report. NATO RTO, Systems Concepts and Integration Panel. NATO RTO: Neuilly-sur-Seine Cedex.
- [12] Curran, M. (2005). UAVs: A Critical Multiplier for Current and Future Forces. RUSI Defence Systems, Summer 2005. pp. 64-66. London, Royal United Services Institute.
- [13] Francis, M.S. and Hirschberg, M.J. (2005). J-UCAS: Inventing a Weapon System for the Information Age. RUSI Defense Systems, Summer 2005. pp. 68-71. London, Royal United Services Institute.
- [14] Hoogeboom, P., Herpfer, E., Fournet, P., Canafoglia, G., de Carvajal, A. and Hofkamp, C. (2005). SOSTAR, A European system for airborne ground surveillance. The Hague: TNO Defence, Security & Safety.

2.1.4 Command and Control

A recent analysis of C2 taken from an HF perspective, holds that C2 is rooted in the authority, responsibility and will of the human commander, including the human use of C2 systems [1, see also 2,3]. C2 is traditionally viewed from a technology perspective as a set of networking, information processing, and computational problems. As an organisational structure, C2 reflects the chain of command and concerns the delegation of authority and the expectation of responsibility and accountability. The chain of command is an important mechanism for accomplishing the transmission of commander's will. It is a process of C2 by which commanders exercise authority over forces to plan and direct operations. A key conclusion from this analysis is that C2 is fundamentally a human-centric undertaking, shaped by the nature of the military mission, by the security environment, and by the fundamental culture of the military itself. The concept of C2 centres around the actions of a commander who has been designated the authority to carry out those actions in respect of resources and subordinates, and who is expected to take responsibility for proper use of that authority. In this perspective, UMV technologies are command support tools and systems, and a vital aspect of C2. Thus, the underlying purpose of technology, such as UMVs, is to extend human capability – “whether it is the physical ability to act in the operational environment, the intellectual ability to make better decisions faster, or the interpersonal ability to communicate with distributed subordinates and security partners”. The challenge is to ensure that UMV technologies are properly integrated with all aspects of C2 systems, but in particular, the human-centric nature of C2, so as to support efficiently and effectively the commander's

authority, and expectations of responsibility and accountability. For further detailed discussion of HF aspects of UMV C2 requirements and broader system-of-system issues, see Chapter 4.

2.1.4.1 NATO Air Command and Control System

The C2 of NATO air forces including manned and uninhabited aircraft and missiles, C2 centres, communications and sensors (and Command, Control, Communication, Computers, Intelligence, Surveillance and Reconnaissance – C4ISR) is performed by NACCS. NATO SCI-124 has considered the importance of NACCS for C2 of UAVs [4]. UAV systems are currently not part of the NACCS and are not managed as part of a manned strike package. In future systems, SCI-124 has concluded that UAVs will need to be closely integrated in the NACCS with manned aircraft if they are to operate in the same force package. Therefore, integration with NACCS needs to be considered in the broad concept of use for UAV systems.

NACCS is a hierarchical structure of headquarters with the operations centres of the System Command (SC) at the top and operations centres of the executing units at the bottom (Figure 2-1). This hierarchical structure consists of three levels: a planning level, in which the commanders deal primarily with the allocation of targets, objectives, resources and areas of responsibility to subordinate commanders; a tasking level, in which the commanders deal primarily with the assignment of tasks to resources for execution; and an execution level, in which the commanders deal with the control and management of the execution of assigned tasks. Four entity types Combat Air Operations Centre (CAOC), Air Control Centre (ACC), Rapid Air Picture (RAP) Production Centre (RPC) and Sensor Fusion Post (SFP) constitute the “core” of NACCS. Integration of UAV operations into NACCS has impact on UAV operations planning, tasking, tactical control, detection and tracking, identification, in addition to data transmission, data dissemination, and airspace management and traffic deconfliction.

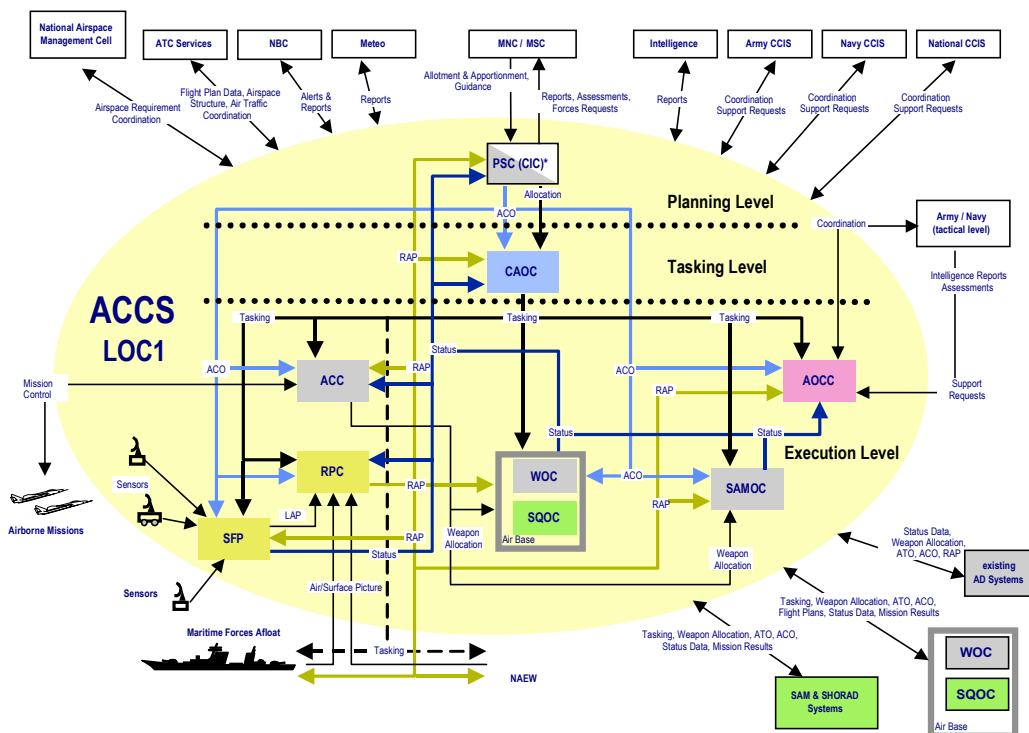


Figure 2-1: NATO Air Command and Control System – NACCS.

NATO SCI-124 have identified that NACCS will disseminate tasking information to all UAV operating locations. UAV sorties must be included in the Air Task Order (ATO) along with manned aircraft sorties for maximum combined effectiveness. NACCS will support coordination of UAV operations with manned aircraft and ground-based defences, including real-time C2 of UAV in-flight activities, and a command, control and communications interface between the NACCS entity and the UAV Control Station (UCS).

2.1.4.2 Interoperability

Interoperability is needed in Combined/Joint services operations to provide close co-ordination, the ability to task quickly available assets, and the rapid dissemination of resultant information at different command echelons. Current and legacy UAV systems are not interoperable. They do not have standard interfaces between the system elements, nor with C2 and ISR systems. NATO STANAG 4586 [5] seeks to define the standards for key system interfaces and functions in the UCS to communicate with different UAVs and their payloads, as well as different C2/ISR systems, to achieve levels of interoperability required by the system's CONOPS. STANAG 4586 includes a human-computer interface (HCI) style guide on best-practice. Multiple levels of interoperability are feasible among different UAV systems. Maximum operational flexibility can be achieved if the UAV systems support the following levels of UAV system interoperability identified by STANAG 4586, based on studies performed by AC/141 (PG/35) and NATO Industrial Advisory Group (NIAG), Sub Group (SG) 53:

- Level 1: Indirect receipt of secondary imagery and/or data.
- Level 2: Direct receipt of payload data by a UCS; where “direct” covers reception of the UAV payload data by the UCS when it has direct line-of-sight with the UAV or a relay device which has direct line-of-sight with the UAV.
- Level 3: Level 2 interoperability plus control of the UAV payload by a UCS.
- Level 4: Level 3 interoperability plus UAV flight control by a UCS.
- Level 5: Level 4 interoperability plus the ability of the UCS to launch and recover the UAV.

To be interoperable to a particular level, the UCS shall be compliant with all the requirements stated for all the levels up to that which is desired.

2.1.4.3 References

- [1] HUM, (2005). HUM White Paper: Sciences of Command and Control. TTCP Technical Report, TR-HUM-16-2005, 30 September 2005.
- [2] Pigeau, R.A. and McCann, C. (2000). Re-defining Command and Control. In: C. McCann and R.A. Pigeau (Eds.), *The Human in Command: Exploring the Modern Military Experience* (pp. 163-184). New York: Kluwer Academic/Plenum Publishers.
- [3] Pigeau, R.A. and McCann, C. (2002). Re-conceptualising Command and Control. *Canadian Military Journal*, 3(1), 53-63.
- [4] NATO, (2005). NATO SCI-124 Task Group, *Architecture for the Integration of Manned and Unmanned Air Vehicles*, Final Report. NATO RTO, Systems Concepts and Integration Panel. NATO RTO: Neuilly-sur-Seine Cedex.

- [5] NATO, (2001). STANAG 4586 Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability, NATO Military Agency for Standardisation, Draft Version 2.4 September 2001.

2.1.5 Legal and Moral Issues

Air Chief Marshall Sir Brian Burridge has expressed concerns about how international law may interpret the legality of future warfare reliant on robotic operations. During his closing address to the ‘Iraq 2003 – Air Power Pointers for the Future’ conference, the Air Chief Marshal presented his views on the use of UCAVs in combat, with the following observations:

“When we go into combat, we have got to be sure what we are doing is both legal and moral. I do not believe that, in future, even though technology will allow it, we will be allowed to indulge in robotic warfare. I simply do not see the international community regarding that as an appropriate way to fight. The notion of using UCAVs controlled from 10 time zones away to prosecute a battle is not something international law of the future will regard as acceptable. I think the notion of a person in the loop, the notion of positive ID, the notion of someone feeling the texture of what is going on in the battlespace, is going to be more and more prevalent.....Overall, I think robotic warfare drives you away from what I term as emotional connectivity with the battlespace. My view is that winning the hearts and minds battle with the indigenous population requires this emotional connectivity” [1].

Kennett [2] provides a detailed analysis of the legal and moral issues of fully autonomous UCAV operations. This analysis observes that the rapid technological advances mean that the concept of UCAV operating in a fully autonomous mode, engaging enemy targets without human interference, is nearing reality. It considers the implications in terms of technological plausibility together with the legal and moral aspects. This leads to the conclusion that although technology may allow waging a war which is free of risk, there are significant legal and moral hurdles, which will need serious consideration throughout the development of such systems. Consideration of the technological viability and legal constraints suggests that a “human-in-the-loop” system will be the most likely mode of operation.

The analysis considers use of UCAVs in combat with focus on the method of supervision of autonomous operations. It asserts that there is a need to determine precisely what that level of supervision entails in conflict and how best to ensure that the human supervisor can interact efficiently and effectively with his uninhabited “charges”. The argument considers that the possibility of highly reliable automatic target recognition (ATR) capability allows the technical possibility of fully autonomous target engagement. High levels of autonomy are projected for future UCAV operations. Indeed, the analysis quotes from informed sources that it will be technically feasible for UCAV to prosecute an attack fully autonomously with ATR when communications breakdown prevents human supervision and authorisation – but the question remains, “what would happen, for example, if during the period of lost communications the context of the conflict shifted significantly?” Surrender, shift of allegiances of major actors and renewed targeting intelligence are cited examples. It follows that the legal requirements for discrimination and humanity and accountability will always require that a human authorises the final decision to attack.

2.1.5.1 Legal Issues

The Law of Armed Conflict (LOAC) is a part of International Humanitarian Law. International Humanitarian Law is a combination of treaty law (binding on signatories) and customary (binding on all). Treaty law requires that for new weapon systems, *at all stages of development*, there is an obligation to determine whether its employment would in some, or all circumstances be prohibited by the protocol or by any other rule

of international law. All weapons systems must undergo a thorough legal review before entry into service. Legal advice is needed to ensure that not only that the end product has some utility, but also that no prohibitions exist as to the actual development of certain weapons. Kennett quotes Best [3, p. 62]:

“The history of warfare has been repeatedly punctuated by allegations that certain new weapons are ‘unlawful’, because in some way unfair by the prevailing criteria of honour, fairness and so on, or because nastier in their action than they need be.”

The development and ownership of UCAV platforms is unlikely to become an issue. What is important, Kennett argues, is that in the case of UCAVs, *the regulations and limitations concerning its use require legal review*. Like guns, they are not necessarily illegal, but there are restrictions on who can own them, for what purpose and how they are employed. The use of UCAVs in conflict is similar to that of a manned platform. However, the major difference is that

“with a manned platform the pilot acts as additional layer of authorisation and he is ultimately held responsible for the outcome of his actions”.

Thus what the level of UCAV supervision entails needs legal review in the areas of discrimination, humanity and accountability.

2.1.5.2 Discrimination

The pilot is required to discriminate between what is a valid military target and what is not. Kennett [2] discusses how information is interpreted with reference to the “feel” of the situation, which would be difficult to replicate in machine information processing. This concerns naturalistic decision-making, where decisions are based on cognitive recognitional processes, involving pattern recognition, implicit and explicit knowledge, appreciation of meaning, visualisation and judgement skills, acquired previously through experience with similar situations.

“To do this, the pilot has a great deal of information available to him, some of which can only be interpreted by the ‘feel’ of the situation, which is sometimes referred to as the sixth sense. Whilst it would, in theory, be possible to harness the ability for a computer to add “feeling” to a decision through a knowledge base, it is unlikely that such a system could be fully trusted to deal with every eventuality. Additionally, proving that such a system is robust would be an enormously difficult task”.

It is believed that the legal requirement for discrimination is one that will be vitally important in the development of autonomous UCAVs. The concept of discrimination emerges from the Additional Protocol to the Geneva Conventions (Protocol 1), which states that:

Article 51(1): “The civilian population and other civilians shall enjoy general protection against dangers arising from military operations.”

Additionally:

Article 51(4): “Indiscriminate attacks are prohibited. Indiscriminate acts are:

- (a) Those which are not directed at a specific military objective;
- (b) Those which employ a method or means of combat which cannot be directed at a specific military objective; or

MILITARY RELEVANCE

- (c) Those which employ a method or means of combat the effects of which cannot be limited as required by this protocol; and consequently, in each such case, are of a nature to strike military objectives and civilians or civilian objects without distinction.”

This means UCAV development having to provide a capability to carry out some form of target identification to ensure discrimination between civilian and military targets. Developments in ATR seem certain to provide a robust capability against traditional military targets and camouflage tactics, but in modern asymmetric warfare, well-organised belligerents ignore the legal requirement under international law to be readily distinguished from the civilian population. They merge with the civilian population, they do not travel in identifiable military vehicles and they use sophisticated deception tactics. Also, military vehicles may be used as decoys to deliberately cause civilian harm, to attract public opprobrium against indiscriminate “aggressors” and to garner further public support for their belligerent causes. Thus, in modern warfare, it is very difficult for an autonomous machine to discriminate between civilians and military targets. Experienced human judgement is needed to assess complex risks, to consider both the immediate and broader context, to judge the consequences and implications of action, and if possible, to anticipate, see through and counter any new deception tactics. Consequently, any autonomous system will remain dependent upon ‘human-in-the-loop’ targeting decisions, where a human makes the ultimate decision to engage a target.

2.1.5.3 Humanity

The concept of humanity, like discrimination, also emerges from the Additional Protocol to the Geneva Conventions (Protocol 1), which states that:

Article 35, (1): “In any armed conflict, the right of the parties to the conflict to choose the method or means of warfare is not unlimited.”

and:

Article 35, (2): “It is prohibited to employ weapons, projectiles and material and methods of warfare of a nature to cause superfluous injury or unnecessary suffering.”

The 1980 Convention on Certain Conventional Weapons is the only instrument that actually prohibits or restricts the use of certain types of conventional weapons. Currently, this covers non-detectable fragments, mines, incendiary weapons and blinding laser weapons, but it is intended to be capable of evolving as technology and international opinion develop. Kennett suggests that as autonomous control techniques develop, their use probably will be subjected to a fair degree of scrutiny and restriction through this convention. It would be logical, therefore, to allow for flexibility in their concept of use as designs for autonomous UCAVs progress. This is a further reason why these systems should retain the ability for the human-in-the-loop to make the targeting decision.

2.1.5.4 Accountability

Kennett [2] argues that the most compelling reason for maintaining the human-in-the-loop targeting decision, is probably the requirement for accountability. International humanitarian law exists so that those who fail to respect the laws are open to legal reprimand. In combat, individuals are accountable for their actions. Accountability forces an operator to ensure that specific RoE are met before the initiation of any hostile action. Failure to adhere to RoE is likely to result in legal action against that individual.

With fully-autonomous UCAVs and without a human-in-the-loop, it is unclear who would be held accountable should things go wrong. Kennett asks: “*Is it the designers, the software writers, the commander who tasked the*

mission or the individual responsible for “supervising” the autonomous machine? Accountability might not be an issue were very highly reliable machines to be possible that do not make mistakes, but as discussed previously the possibility of enemy deception can not be discounted.

The 1922 Hague Rules of Air Warfare, which contains much customary law, states that “A military aircraft shall be under the command of a person duly commissioned or enlisted in the military service of the State; the crew must be exclusively military”. This rule originally concerns the use of civilian crews to operate military aircraft. However, the underlying assertion that “military aircraft must be under command” is one that could apply specifically to UCAVs. This has significant implications for accountability. As noted earlier, it will be technically feasible for a UCAV to prosecute an attack fully autonomously with ATR when communications breakdown – but this means being willing to trust the UCAV to determine whether RoE are met – in effect, for it to continue its mission with nobody in command. This is to persist with loss of human sensitivity to shifts in context, and any resultant possibility of doubt about engagement, which would probably cause the human not to engage. Kennett notes: “*It is hard to imagine a machine that has doubt, especially after meeting pre-programmed criteria such as probability of identification and particularly when major shifts in context occur*”. He postulates that “the reaction of the international legal community to the prospect of autonomous UCAVs continuing missions when communications have been severed and thus the vehicle is not under human command, is likely to be severe”.

2.1.5.5 Legal Implications

Kennett [2] indicates that whether by customary international humanitarian law or treaty law, military forces must ensure that the requirements of discrimination and humanity are met and that a degree of accountability exists. The following conclusions are drawn from the analysis:

- Technology is moving rapidly to a point where the requirement of discrimination could be met to a high degree of reliability.
- This technology will be of limited utility against an enemy who is deliberately willing to blend into the surrounding civilian population.
- The ownership of UCAVs may be transparent to the concept of humanity, but their use is likely to attract close scrutiny in any forthcoming conflict.
- As the number and type of autonomous combat machines increases, it is unlikely that the international community will accept such proliferation without insisting on new legislation to limit or restrict their use.
- Accountability will remain one of the key tenets of future conflict, and whilst autonomous combat machines promise much, it is likely that humans will always be required to make decisions where humans may perish.

2.1.5.6 Moral and Ethical Issues

The study of moral issues (ethics) is “*concerned with or relating to the distinction between good and bad or right and wrong behaviour*” (based on the definition of ‘moral’ from the Oxford English Dictionary). In considering moral issues of using autonomous UCAVs, Air Chief Marshall Sir Brian Burridge refers to the term “*morality of altitude*” that was coined in to reference the disconnection of the pilot at 10,000 feet from the destruction caused by bombing on the ground [4]. This disconnection led to a lower incidence of psychological problems amongst USAF pilots than their US Army colleagues on the ground during the Vietnam conflict. He believes that the “*morality of altitude*” is at the heart of the debate of how international

MILITARY RELEVANCE

law will interpret robotic warfare in the future. He concludes that *“Feeling the granularity of the battle-space is the key issue in interpreting the Rules of Engagement”*.

The Air Chief Marshall poses the future possibility of the “Play Station” operator who may never have had actual combat experience, no connections with other operational units, and no shared operational experiences [4]. Furthermore, he expects that future highly autonomous systems will be reliant on an experienced programmer for their autonomy, who may not have any experience of combat operations in a manned platform. He notes that this will *“further remove the remote pilot from the system and place him within the industrial or military support base”*. The Air Chief Marshall discusses how this exacerbates *“the disconnection of air power from the shared battle-space”*. In considering the increasing lethality and persistence of UAVs, he questions how we stop the “Play Station” generation becoming the *“playground bully”* of the battlefield? He asks if this disconnection exacerbates the potential for the *“play ground bully”* in all of us to emerge. He contrasts the simplicity of *“drop and drag”* mouse actions on a lap top during remote reach-back operations, with the consequences on the other side of the world.

This discourse has some resonance with the social psychology of obedience and capability for human to act callously when disconnected from suffering and under pressure from authorities to inflict harm [5,6]. Milgram famously created a memory and learning experimental situation in which volunteer subjects believed they were administering electric shocks of increasing severity to another individual, as punishments for mistakes in two word pair reading lists. No shocks were actually administered, but the subjects were made aware of the discomfort caused by poundings on the wall. Quoting Milgram: *“With numbing regularity good people were seen to knuckle under the demands of authority and to perform actions that were callous and severe..... A substantial portion of the people do what they are told to do, irrespective of the content of the act and without limitations of conscience, so long as they perceive that the command comes from a legitimate authority”*.

Drop and drag mouse actions at remote UAV control stations seem even more dissociated from their effects than Milgram’s electrical switches. Unless the “Play Station” generation can somehow avoid *“the morality of altitude”* and *“feel the granularity of the battle-space”*, we probably should not be surprised if they have the potential to become the *“playground bully”* of the future battlefield, and find UGV operations running into conflict with international law.

Kennett [2] reviews the argument for the morality of using autonomous UCAVs to kill without risk. This analysis concludes that, in some circumstances, even though technology and the law will allow such acts, morally, it would be indefensible. The analysis begins by recognising that killing in conflict presents a moral dilemma and that there is no universally accepted view of the truth. Feeling or subjectivity, as opposed to reason, largely determines the moral justifications – whether it feels truly right or wrong. The ethical implications will be dependent on the situation, ranging from supreme emergency to war of choice. In a war of choice, what is morally acceptable behaviour will be comparatively restrictive and judged on a sliding scale of necessity in the socio-political rather than legal sense. Using UCAVs in a war of national survival will be morally acceptable. During a war of choice, pitted against a technologically inferior opponent, using UCAVs will be acceptable for attacking targets that represent either an imminent or clearly identifiable latent threat (ballistic missiles, WMDs, massed armoured forces) – but although legally justifiable, it would be more difficult to feel justified attacking small groups of military personnel with UCAVs, decided by operators who, as Burridge [4] describes, are *“10 time zones”* away, removed from the threat, free of risk and without *“the emotional connectivity of the battlespace”*. Kennett adds *“to open fire and to take life in such a situation does seem somewhat unsporting, even in warfare”*. What emerges is that the taking of life, at a time and place of ones own choosing entirely without risk, although legally acceptable in war, is morally unjustified. There has to be an emotional connectivity with the decision, arising from having to endure feelings of risk, sufficient

to consider whether the decision feels right... *“Having to endure risk indicates no choice but to be emotionally connected to the battlespace”*. It does not sound right to be able to wage war, risk free, through the virtue of technology, and in the course of doing so, to kill regularly so that killing becomes a de-personalised act. The analysis concludes:

“There will always be times when killing without risk in conflict will be necessary and entirely justifiable. However, outside the boundaries of fighting for national survival, such acts should not become the norm. To allow this would be morally wrong and risks devaluing the serious nature of conflict through a lowering of the moral value of killing and the value of human life”.

2.1.5.7 References

- [1] BurrIDGE, B. (2004). Iraq 2003 – Air Power Pointers for the Future – Closing Address. Air Power Review, Vol. 7, No. 3, pp. 1-15.
- [2] Kennett, P.D. (2005). Autonomous Killing Machines – The Technical, Legal and Moral Implications. Defence Research Paper, Advanced Command and Staff Course No 8, September 04 – July 05, Joint Services Command and Staff College, March 2005.
- [3] Best, G. (1983). Humanity in Warfare: The Modern History of the International Law of Armed Conflicts, London: Methuen & Co.
- [4] BurrIDGE, B. (2005). Post-modern warfighting with unmanned vehicle systems: Esoteric chimera or essential capability. RUSI Journal, October 2005, 150 (5). London, Royal United Services Institute.
- [5] Milgram, S. (1963). Behavioural study of obedience. Journal of Abnormal Social Psychology, Vol. 67, pp. 371-378.
- [6] Milgram, S. (2004). Obedience to authority: An experimental view. New York: Harper Collins.

2.1.6 UMV Use Cases

An articulation of the context of use of UMV systems is needed in order to provide a military relevant reference basis for considering HF issues. Use cases can be derived from existing representative military scenarios and associated “*snapshots*” or “*vignettes*”. Military scenarios are ways of characterising future military threats and challenges. Scenarios are tools for operations analysis. They provide a means for evaluating capabilities and capability gaps, investigating military effectiveness and estimating cost/benefits for investment appraisals. In addition, scenarios are tools for systems engineering, providing the basis for the mission analyses used to develop understanding of system functions, information and user interface HF requirements. The selection of vignettes is important and entails the inherent risks of being unrepresentative. Selectivity risks biasing analysis, by introducing irrelevant or limiting focus, and setting overly restrictive boundaries and limitations to thinking. On the other hand, representative use cases, obtained from credible and knowledgeable sources, provide an efficient and effective means of communicating requirements and sharing understanding on likely contexts of use. This is particularly valuable for considering the relevance of new concepts and technologies. Development of system engineering requirements for UMVs is beyond the scope of the work of HFM-018. The purpose of this report is to provide a basis for discussion of scientific research on UMV technology and associated HF issues. Use cases are provided here to communicate likely contexts of use for appraisal of the military relevance of scientific and technical content of the report in the chapters that follow.

MILITARY RELEVANCE

2.1.6.1 UAV Use Case

Military Applications Study NATO SAS-016, Future Operations with UAV Systems and SCI-124 on UAV C2 Architectures, have developed a Peace Support Operations (PSO) scenario to describe understanding UAV roles [1]. The PSO scenario is considered to be suitable reference use case for the air component of HFM-018 work. It is derived from a high level Peace Enforcement scenario and set during an early phase of the overall NATO operation. NATO forces conduct major air operations (offensive, defensive, support) using Composite Air Operations (COMAO) conducted from a Combined Air Operations Centre (CAOC). The COMAO aims to maximise the impact of a given force by concentrating efforts and enhancing survivability. This is achieved through mutual support, best available use of assets and saturation of air defences. The challenges are primarily from integrated air defences. This phase of the COMAO is illustrated in Figure 2-2 below. Figure 2-2 depicts the initial forced entry of NATO amphibious and airborne forces into the crisis area, the establishment of safe deployment areas and facilities, and the deployment of lead elements of the main PSO force and supplies into those areas.

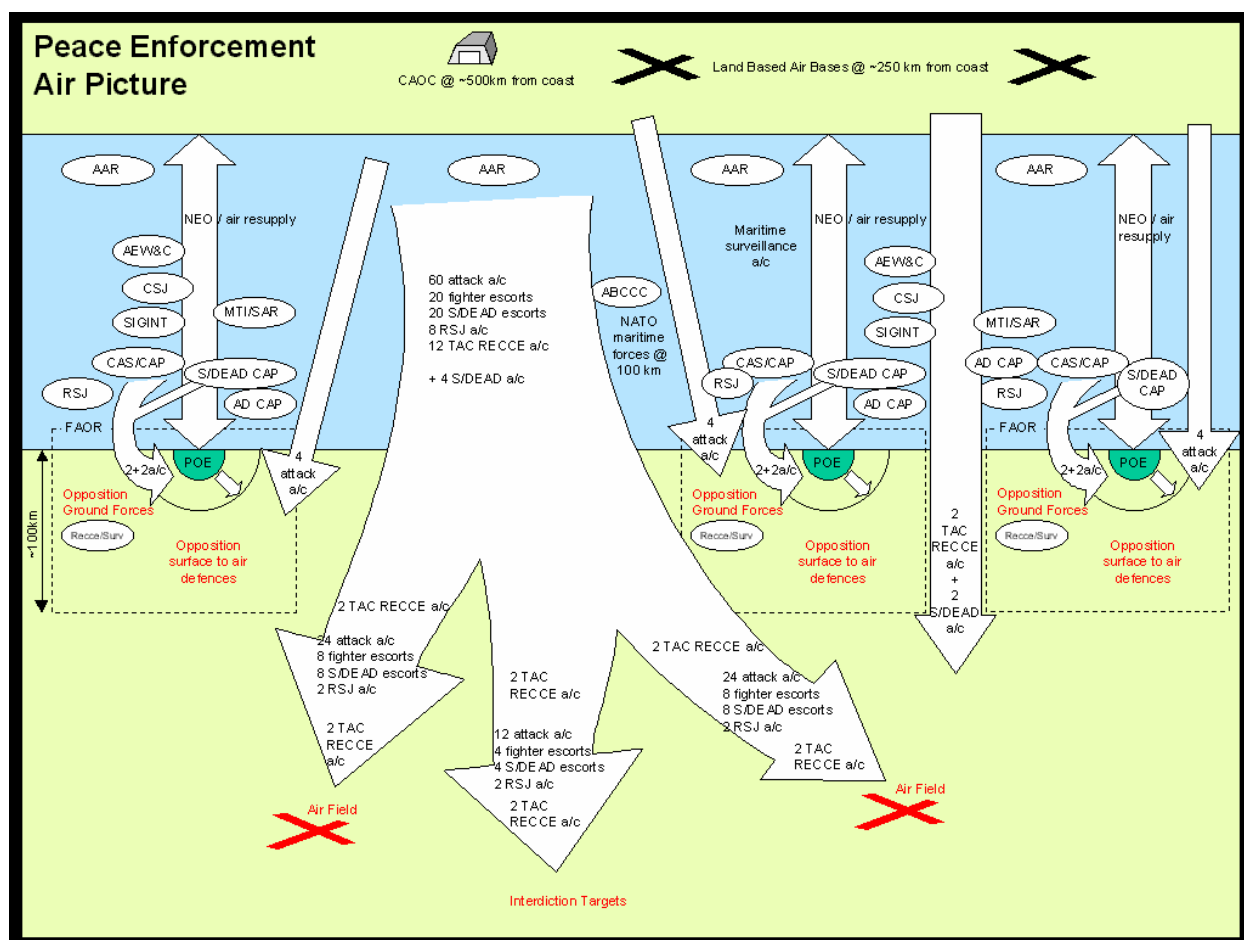


Figure 2-2: Peace Enforcement – Peace Support Operations at COMAO Level.

During this phase NATO forces seize and hold seaports and airports to be used for entry. At the end of this phase all entry forces have been deployed into the crisis country and the entry zones/bridgeheads are secure.

The operational scenario covers a limited period of time (10 days). During this time the various operations and missions take place. Although it is derived from the high level scenario, certain aspects of the operational scenario have been generalised in order to avoid making it too geographically and threat specific. At the time at which this 'snapshot' operational scenario is set the three main landing areas have been established and NATO forces have advanced up to 25 km from the entry zones.

The over-arching objectives which NATO air power must accomplish and the tasks and functions it must perform in the operational scenario are as follows:

- Neutralisation of the internal air threat (No Fly Zone);
- Defensive counter air operations;
- Offensive counter air operations against air bases;
- Neutralisation of ground-based threats to air traffic;
- Radar support jamming;
- Hard kill's/DEAD;
- Communications jamming support;
- Offensive Air Support for NATO entry forces and lead elements of the main PSO force;
- Deep interdiction of opposition ground combat power;
- Neutralisation of the maritime threat;
- Battlespace surveillance, airborne command and control and communications support;
- Air surveillance;
- Ground surveillance and reconnaissance;
- Maritime surveillance and reconnaissance;
- Battlefield tactical command and control;
- Re-supply of NATO forces;
- Emergency non-combatant evacuation;
- Combat Search and Rescue; and
- Psychological operations.

NATO forces must also deter intervention and attacks by states neighbouring the crisis country. As such, NATO air power is also held in readiness to deal with air and ballistic missile attacks from these neighbours, to interdict any ground attack, and to conduct operations for strategic effect against them. However, at the time at which the operational scenario is set no attacks have been launched by these neighbouring states. Consequently all NATO air activity in the snapshot operational scenario is related to the main Peace Enforcement operation in the crisis country.

The air defence and offensive air capabilities of the opposition forces have been substantially degraded by the time of this operational scenario. However, the opposition air defences have not attempted to mount a full-scale challenge to NATO offensive air operations. Similarly, the opposition has conducted only limited offensive air operations. Rather the aim of opposition air defence and offensive air operations has been to

MILITARY RELEVANCE

inflict losses on NATO forces that although of limited military operational and tactical significance, the opposition believes will have direct strategic and political impact.

As a consequence the opposition has sought to preserve his air defence and offensive air capabilities by avoiding large-scale engagements, and by trying to make his forces difficult to locate and target. Consequently, at the time at which this operational is set, the opposition forces still have some air defence and limited offensive air capabilities.

2.1.6.2 Integration of UAV and Manned Aircraft Systems

UAV currently operate in segregated airspace physically separated from manned aircraft. SCI-124 report that this is due to the lack of clearance to operate in conjunction with manned aircraft and other UAVs, and overall inexperience with UAV operations. Integration with manned aircraft in the same airspace will soon be enabled by technological advances. Currently, the most common role for UAVs is ISR. UAVs are performing limited strike missions. Dedicated strike UAV platforms are planned for the mid-term timeframe. Therefore, SCI-124 have concluded that there is a definite requirement for the integration of strike UAVs with manned aircraft.

NATO SAS-16 used analysis of the PSO scenario and UAV capabilities to derive conclusions on UAV integration. An illustration of the integration of UAVs into the PSO scenario is shown in Figure 2-3. Different classes of UAV systems can undertake different types of mission/tasks dependent on payload (mass, type), range and endurance, speed and survivability (altitude, speed, signature, defensive aids). Broadly, they conclude that in the mid term UAVs will be able support only a limited range of attack missions. In long term, a wider range of attack missions could be supported, with greater autonomous operations, and tight rules of engagement, involving human-in-the-loop during target engagement phases. At the mission level, concepts of employment will depend heavily on mission and UAV system type. UAV systems can replace manned aircraft for various mission/tasks, placing fewer aircrew at risk. UAV systems can complement manned aircraft to enhance effectiveness of manned attack missions. They can perform high risk, high pay-off missions/tasks. Also, long endurance UAV systems can support more than one mission.

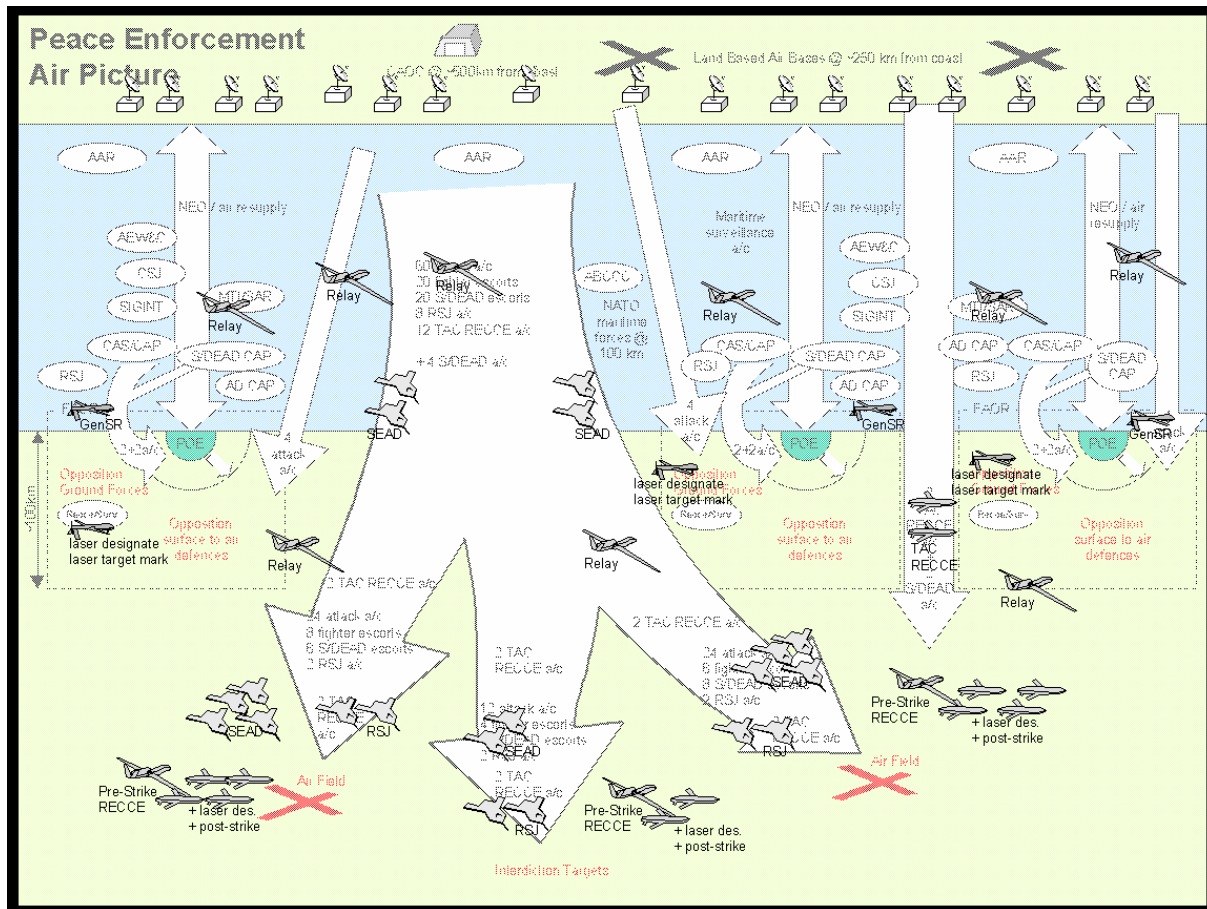


Figure 2-3: Integration of UAV Assets in PSO COMAO.

NATO SAS-16 concluded that many concepts require close co-ordination between the UCS and manned attack aircraft, but close co-operation is already needed on manned aircraft missions [1]. Some concepts involve hand-over of control to manned aircraft. Where hand over occurs multi-crew types offer a better option, and there is a risk of overloading the mission crew on airborne C2 platforms. Data links to the UCSs are a key issue and weakness (jamming). Beyond-line-of-sight requirements and latency problems add complexity, when detailed control is required. C2 authorities will need assistance to maintain the air picture. For the mid-term, there will be no close formation flying because of technical limitations and aircrew mistrust. Special corridors will be needed for ingress and egress, with rendezvous with manned aircraft in pre-planned areas. Special operating areas will need to be identified. Longer term, there will be greater formation coordination and integration with manned aircraft, since manned aircraft will remain in service for many years, and integration with the C4ISR system.

For COMAO mid term, SAS-016 observed that UAVs can replace various manned aircraft missions, but not those involving close formation coordination. UAV systems will use assigned corridors (routes and flight levels). UCSs will need to be integrated into the COMAO planning process. This will include consideration of: assignment of UAV mission leaders; routing (rendezvous areas and procedures, timings, air traffic procedures); reaction to threats; target area tactics and procedures; delay and cancellation procedures and options; communications and data link selection and de-confliction, including beyond-line-of-sight

MILITARY RELEVANCE

requirements; UAV handover procedures where appropriate. The potentially large number of UCSs will need rationalisation and standardisation of the ground segment of UAV systems. UCS standardisation has been undertaken through STANAG 4586 activities [2]. Current COMAOs with manned aircraft require extensive pre-planning and have a degree of rigidity. The introduction of UAVs will shift the workload, but should not necessarily lead to overall increases. Longer term, UAV systems for attack missions (UCAV) will not need support, and there will be reduced demand for COMAO. Surveillance and reconnaissance UAV systems will form an integrated part of the overall C4ISR system. Direct links to offensive air operations will reduce the decision loop times of the sensor-to-shooter system. At the operations level, UAV system planning will need to be incorporated at the CAOC/Air operations level (Air Tasking Order – ATO; Airspace Control Order – ACO; Airspace Control Measures – ACM)). As a cautionary observation, SAS-016 noted that UAV systems may lend themselves to micro-management from higher command levels.

HFM-018 work on a human-centric framework for control of UAV operations required a degree of more detailed task specificity than provided in the PSO use case. The following UAV tasks were identified for a COMAO mission to attack an airfield in Article V operations, derived from SCI-124 analyses [1].

Ingress

- Control, Guidance, Navigation (ownship and attack aircraft);
- Replan;
- Communication (C2 MC, attack aircraft, other UAV UCS);
- System management (+contingencies);
- Self defence; and
- Target location.

Over Target

- Target registration, identification, verification, designation (for attack aircraft);
- Control, Guidance, Navigation;
- System management (+contingencies);
- Communication (C2 MC, attack aircraft, other UAV UCS);
- Sensor management;
- Self defence;
- Rules of engagement; and
- Battle damage assessment.

Egress

- Control, Guidance, Navigation;
- Communication (C2 MC, attack aircraft, other UAV UCS);
- System management (+contingencies); and
- Self defence.

2.1.6.3 UUV and UGV Use Cases

For the purposes of this report, the VSW MCM role provides a commonly recognised use case for understanding the application of UUVs. The basic task structure for MCM can be re-used to apply to UGVs in the MCM/EOD role.

Blackburn et al [3] describe the UUV VSW MCM (and EOD) task as comprising seven phases:

- 1) Deployment and distribution of assets;
- 2) Execution of a search strategy;
- 3) Detection of mine-like objects;
- 4) Classification and identification;
- 5) Neutralisation;
- 6) Verification and certification of clearance; and
- 7) Recovery of assets.

The UGV use case covers MCM and EOD tasks from high tide mark and above, providing route reconnaissance and access in support of troop advancement in the PSO scenario. The following tasks can be considered to apply to UGVs:

- Threat Assessment – close quarter/booby trap and hostile environments;
- Route Opening – approach dependent on collateral damage and speed of advancement;
- Route Clearance – approach dependent on collateral damage and speed of advancement; and
- Casualty recovery and management.

Understanding of how both UUVs and Unmanned Surface Vehicles (USVs) could conduct MCM is described in Carver [4]. This analysis reports that the foremost reason for preferring the UUV to a USV in the MCM role, is the requirement to conduct the mission initially in a covert manner. In many scenarios, it is not likely to be politically acceptable to conduct overt operations in another nation's littoral waters, thus making a semi-submersible UUV equally unacceptable. In any scenario, a variety of tactical options emerge, dependent largely on the level of autonomy given to the vehicle and the ultimate mission objectives. In the MCM role, the UUV will be deployed from a platform, or a harbour, and transit to its operational area. Characteristics of the vehicle associated with this phase include its range, speed and endurance, which must match the expected operational mission and tidal conditions. UUV capability is a function of size. The greater the capability in each area the larger the vehicle will be, unless new technology provides batteries or fuel cells with a greater power density. Once in theatre, the UUV will run along its pre-programmed survey path towards the objective. Dependent upon the vehicle's payload capability, degree of autonomy and rules of engagement, the UUV might then follow one of the following tactical options:

- Report the position of mines and wait for further instructions.
- Autonomously decide no clear path through the minefield exists and search for an alternate route to the objective.
- Dispose of mines along the swept path (from here the covert nature of the mission is lost).

MILITARY RELEVANCE

The required operational role will determine the payload, which will influence the vehicle's size and the power required to complete the mission. In all events, the vehicle will be fitted with an inertial navigation system, collision avoidance sonar and high-resolution mine hunting sonar. Further, net enabled capability (NEC) will be provided by secure AComms. Communications may include the deployment of buoys or returning to the surface to communicate directly. The greater the autonomy given to the vehicle and the use of buoys will help to maintain the covert nature of the mission. Ordnance will need to be carried if the detected mines are to be disposed of.

Various UUV scenarios appear in the open literature. Carver [4] describes how, in the “harbour mine hunt” scenario, a number of small UUVs are launched to search for mines. Because total coverage is so important, the small UUVs would continually verify their position using GPS information provided by a larger communications/navigation vehicle positioned just outside the search area. Once the mines have been located, each small UUV (e.g., ALUV) could position itself over a mine and, after receiving the command, drop a small detonation charge to neutralise the mine.

2.1.6.4 Composite UMV Use Case

For the purposes of this report, HFM-018 (led by Lt Cdr A.G. Carver) have developed a composite scenario snapshot or “vignette”, to provide a UMV use case to illustrate the possible functioning of UMVs. This composite vignette includes space, air, sea and land domains with UGV, UUV and UAV task elements. The tasks are summarised in Table 2-3. The task links are illustrated in Figure 2-4.

Table 2-3: Composite Scenario Tasks

Phases	Domains			
	Space	Air	Sea	Land
Period of Increased Tension	<p>Surveillance of potentially hostile nation (PHN) – satellite to look for indications of hostile intent.</p> <p>Observe forces infrastructure – deploy satellites to observe PHN force dispositions.</p> <p>Observe forces manoeuvres – satellite to conduct survey of PHN forces.</p>	<p>Observe potential landing areas – use UAV to conduct initial survey of potential landing sites.</p> <p>Observe force numbers and manoeuvres – UAV to conduct survey of PHN forces.</p>	<p>Rapid environmental assessment – UUV to make assessments of ship movements and collect environmental data.</p>	
Transition to War	<p>Targeting – satellite to collect targeting data.</p> <p>Update observations.</p>	<p>Targeting – UAV to collect targeting data.</p> <p>Force observation.</p>	<p>Maritime survey – UUVs deployed to conduct more detailed survey of possible landing areas/locations. This could be a beach or a port if not heavily defended.</p> <p>Mine survey – UUV performs route surveys with synthetic aperture sonar. Identify mine like objects in path of route to selected beach head.</p> <p>Beach survey – UUV deploys UGV to gather initial beach survey data ahead of special forces.</p> <p>Port survey – UUV enters port and conducts visual survey of facilities and force disposition.</p>	<p>Targeting – UGV to collect targeting data.</p>

MILITARY RELEVANCE

Phases	Domains			
	Space	Air	Sea	Land
Conflict		<p>Deploy air to ground weapons to destroy strategic and tactical targets – UAVs to carry offensive weapons into theatre.</p>	<p>Mine clearance –</p> <ol style="list-style-type: none"> 1) UUV to continue mine survey. 2) UUV to conduct mine disposal. 3) UUV to provide verification and certification of clearance. <p>Support beach landing – Large UUV to transport equipment and re-supply special forces ashore.</p>	<p>Route reconnaissance for access – UGV deployed to perform route surveys above water line in path of route from beach landing area ahead of special forces.</p> <p>Threat assessment – close quarter booby trap and hostile environments – UGV to identify mine like objects, EOD, and CBRN hazards in path of selected route.</p> <p>Route clearance – close quarter booby trap and hostile environments –</p> <ol style="list-style-type: none"> 1) UGV to conduct mine disposal and neutralise EOD. 2) UGV to provide verification and certification of mine clearance. 3) UGV to provide detection and analysis of chemical, nuclear and biological hazards. <p>Casualty recovery and management – UGV deployed to conduct CSAR, and casualty evacuation.</p> <p>Covert operations – UGV deployed to support of covert operations. Sense and report a personnel and vehicle presence night and day. Report target and platform locations.</p>

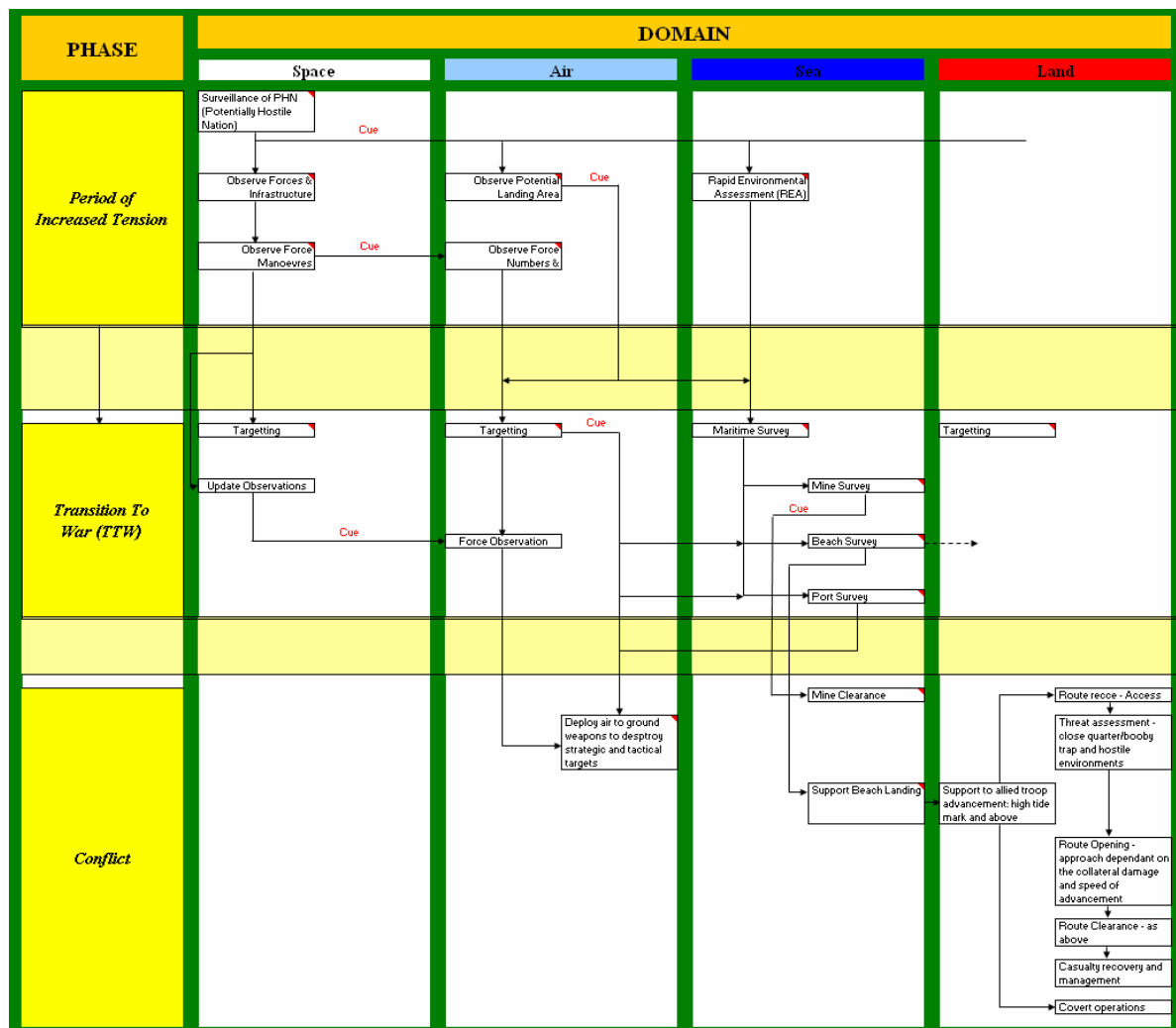


Figure 2-4: Illustration of Composite Scenario Task Links.

2.1.6.5 References

- [1] NATO, (2005). NATO SCI-124 Task Group, Architecture for the Integration of Manned and Unmanned Air Vehicles, Final Report. NATO RTO, Systems Concepts and Integration Panel. NATO RTO: Neuilly-sur-Seine Cedex.
- [2] NATO, (2001). STANAG 4586 Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability, NATO Military Agency for Standardisation, Draft Version 2.4 September 2001.
- [3] Blackburn, M.R., Laird, R.T. and Everett, H.R. (2001). Unmanned Ground Vehicles (UGV): Lessons Learned. Technical Report 1869. SPAWAR Systems Centre, SSC San Diego, CA 292152-5001. November 2001.
- [4] Carver, G. (2004). Some Human Factors Integration (HFI) Issues Arising from the Operation of Unmanned Underwater Vehicles (UUVs). In: Uninhabited Military Vehicles (UMVs) – Human Factors

of Augmenting the Force. RTO-MP-111, RWS-010-OKN1. Proceedings of the NATO RTO Human Factors and Medical Panel Workshop held in Leiden, The Netherlands, 10-13 June 2003. NATO RTO: Neuilly-sur-Seine Cedex. March 2004.

2.1.7 Acknowledgements

The authors wish to acknowledge the contribution in this report of the work of NATO SCI-124 on UAV C2 architectures under the direction of Prof Antony Gillespie (Dstl AWSD Farnborough and Chair SCI-124) and in particular, the assistance in interpreting the relevance of the work for HFM-018 provided by Antony Grabham, Dstl AWSD Farnborough, UK. Liaison with NIAG Study Group 75 was provided by Peter Wilkinson, BAES Military Air Systems, Warton, UK. In addition, we wish to acknowledge the assistance provided in understanding UGV EOD/IED user requirements provided by Nicki Heath, Symbiotics Ltd and Paul Burns, SOE Academy, UK.

2.2 PART II – MILITARY RELEVANCE FOR UNINHABITED AERIAL VEHICLES (UAVS)

2.2.1 Introduction

Technology is a great source of power, which also is the reason why the military righteously is very concerned with it. New techniques create new tools for the human to utilise, new ways for the military to impose force. Together with the development of the logical circuit follows however a significant increase of the rate by which technological systems' ability to do new things increases. Systems are quickly getting performance characteristics that not only depend on concrete physical input, but also on arbitrary and abstract contexts. With the help of the microprocessor and clever programming skills, technology has expanded from advanced mechanics to automated machines that use logic and artificial intelligence. Technology has with that taken the great leap into an area that used to be strictly human business, the world of abstracts.

This development is likely to be just like any other development, humanity will eventually learn how to best use it and certainly benefit from it – but there will always emerge a few solutions along the way that probably would have been better off never being made.

There is however a certain peculiarity about abstracts: everything is more or less interconnected. It's quite impossible to state where one issue ends and the other starts. This means that almost every tiny little abstract rule somehow ends up being dependent on the supreme abstract dilemmas as aim, purpose and eventually even ethics and morale. Hence, it's not as easy to let technology perform only delimited parts of the abstract work as is possible with physical.

Technology will for certain be of great assistance in the traditionally strictly human area of abstracts, but the rules are different. This text argues that abstract tasks performed by technology must be designed with a greater amount of co-operation between human and machine, compared with typical physical work. Automated tasks depending on abstract contexts must be designed with great care. The more abstractly complicated a machine becomes the more thought must be put behind the design of the human role in order to create a machine that will be truly useful, even if the overall context differs from first assumptions.

The main issue for this text is that such thinking is believed to require a minor shift in focus when designing systems: it requires a human-oriented philosophy. Although the tone in the philosophy presented here might indicate that certain things are impossible, that's not the tenor, this is only to bring matters to a head.

Scope: The arguments need to be viewed differently for every context. Human control of a tiny little device working alone does in fact embrace these issues, although only very philosophically – but when it comes to complicated systems affecting really serious matters then this philosophy should have significant implications on just about everything from design to application. When, for instance, it's stated that only humans are allowed to judge in the topmost context and therefore need to be in control, it doesn't say that humans need to do everything. The human may justifiably have countless more or less completely automatic systems doing lots of good work, but this philosophy emphasises that there is an important question about how these systems affect the ability for the human to make sensible decisions and influence the situation.

From the Swedish UCAV study's point of view this material serves as one input among others to the compilation of our theoretical framework. Its purpose is to be a believed necessary counterbalance to the perceived technologically focused UAV community. It should not be seen as an official standpoint.

2.2.2 The Map of Relevance

The entrance of technology into the area of abstracts has introduced the possibility to develop automation, which in turn has made it possible to design uninhabited platforms. These technologies provide a lot of new exciting opportunities, not least for many typical military situations, which tend to be extremes both regarding performance and risk. There is however a significant risk of counterproductive solutions, regarding actual effect in reality. The relative strengths of automation and uninhabited vehicles are quite direct results of platform, vehicle or system characteristics and thus are comparatively easy to spot. The relative weaknesses on the other hand, are mostly more indirect consequences of loss of human control as consequence of conditions created by the characteristics of the systems. These consequential weaknesses predominantly become apparent in situations with significant uncertainties, especially when there are uncertainties in arbitrary abstract dimensions including context and politics, in situations with great complexity and sensitivity. They tend to show up in actual conflict situations where "reality suddenly comes and hit you in the face". Also, the only fixed planning parameter for future conflicts is that there is significant uncertainty about what the situations actually will look like.

To appropriately judge the relevance of anything, both strengths and weaknesses must be known and assessed according to a common ground of values. For something to be military relevant there must be a desired military effect that exceeds the cost of using it. And military effect is nothing but humans influencing other humans using military powers, commonly facilitated by technological systems.

The Map of Relevance consists of a collection of theoretical descriptions of a few believed fundamental conditions in [military] reality including an attempt to describe the subtle but important difference between designed and applied [military] effect. Appropriate effect is the key to relevance and this philosophy argues that the only relevant [military] effect is such that is intentionally achieved by [military] humans, where intentionally meaning being completely in charge of what's happening. If not, then the effect isn't really military and thus has no military relevance. That is, a human in charge is unquestionable and hence the reason to state it as an axiom.

2.2.3 The Human Axiom

The purpose of the human axiom is not to oppose automation and uninhabited systems since these technologies do render important capabilities. The purpose is to provide a foundation for the believed necessary thinking required for developing better systems containing automation. It's based on a human-oriented philosophy emerged from the issue of uncertainty and the theories of control described below.

2.2.3.1 The Philosophy

This philosophy may be interpreted somewhat controversial and is just because of that believed to be relevant. It's intentionally a bit provocative due to the ambition of being an eye-opener and needs to be read with that in mind. Because, it's not fundamentally important whether the word is autonomous or highly automated, whether mankind suffers from ugly technological hysteria or simply is a bit technologically focused, but the philosophy's underlying "crux of the matter", the essence that perhaps isn't really managed to be clearly conveyed, but that hopefully at least is written somewhere between the lines, is still very much the basis for the whole.

Technology exists solely to extend, magnify or complement human abilities. The use of a technological solution is never an end in itself. The purpose is always to serve the human and quite commonly the service is the gain of influence on other people that it provides, which apparently also is why technology is such a highly desired military tool. This influence is exercised either directly with system functionality, which then is the main military way, or indirectly like for instance through economical profit, which is the more commercial or political way. Either way, it is the humans who invented technology, it was done to serve the humans and technology has no own free will. That is, technology has no reason for existence on its own, it should never be an end in itself.

The modern world however, appears to be suffering from something that may be labelled technological hysteria. The disease proves itself as constantly creating a competition between technology and humans, by the rules of technology. Performance is judged according to what the technology is designed for and human participation is then excluded since technology is found to perform better. This may be the case when leaving out the fact that some odd quirks of life called reality most certainly will pop up and fundamentally alter the situation, not unlikely into something that the technology wasn't designed for. Then the drawback becomes clear. The human has no possibility to interfere when excluded from participation and the device that was meant to be helpful may instead cause severe problems. The aim in designing these systems should therefore be to allow for a natural interaction and cooperation between the human operator and the technology. Over-explicitly, technology should take care of details and the human should do the thinking and planning, although very well served by a lot of details handed by the technology.

This hysteric disease tends to end up in the technological imperative, what is possible is a must. Where it's possible to replace human appearance it's done. The healthy approach would instead be to investigate where and, equally or even more important, how technology best could help the human. Since technology doesn't strive for it by itself, this, what from a human perspective must be seen as a clearly unfavourable order, is maintained by the humans themselves, which solely is a reason good enough to call it hysteria.

The complete hysteria is reached when the aim is to develop autonomous systems, since autonomy means self-governing. And ultimately, for anything to be truly autonomous it must be able to raise mutiny and even to decide for its own set of reasons to kill its commander. That is obviously not what mankind wants with its technological solutions. The highest form of automation is not necessary autonomy since that implicitly implies loss of control, which is a considerable price to pay. Furthermore, automation is always automation and it has no private desires or personal values that may constitute truly autonomous decisions. The highest form of automation should therefore be designated nothing else than completely automatic systems, although the automation may be very advanced and contain all sorts of artificial intelligence. Furthermore, automatic does not necessarily mean without human interaction since a system can very well be simultaneously highly automated and very interactive. The character of the interaction is probably the core issue for the possibility to maintain control of systems with automation containing complex abstract rules. Advanced automation and

highly automated systems create great prospects, but technology must always and unconditionally serve the human and thus be completely under some humans' control, which means it should never be autonomous!

Although this phrasing argumentation may seem like splitting hairs, it does serve a specific purpose. The word "autonomy" is perhaps most commonly used to denote something that is more than "just" automatic, something that is as independent as possible, which might be a completely correct use of the word. But, independent need not necessarily imply uncontrolled, which the technological hysteria tends to impose. It is the use of the word autonomous together with the competitive environment between humans and technology caused by this technological hysteria that makes it dangerous. This argumentation illuminates among other things the subtle but important difference between autonomous, as in independent and unconstrained, and automatic, as in independent within certain limits.

This philosophy is virtually nothing but a slight rephrase of Isaac Asimov's famous three "laws of robotics" from 1942, or four, since he wrote the zeroth law in 1985. The phrase "robotics" is easily identified as being identical to automated systems, and these laws are:

- First: A robot may not injure a human being, or, through inaction, allow a human to come to harm;
- Second: A robot must obey the orders given it by human beings except where such orders would conflict with the First Law;
- Third: A robot must protect its own existence as long as such protection does not conflict with the First or Second Law; and
- Zeroth: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.

One common objection to these laws is that they inhibit the use of "robotics" as tools for police and military work, since such inevitably include the use of force that sometimes deliberately harm human beings. According to this philosophy should a rephrase then be that robots, i.e., automation, must never autonomously violate these laws. If they are to be violated, there must be at least one human being in charge, which has control, of what the automation is doing. Hence, the automation must never be autonomous, in the word's full sense.

2.2.3.2 The Automation Paradox

One core thing that fundamentally separates human intelligence from the artificial counterpart is the fact that the human has the unique ability to always be able to apply everything in a greater or different context. Artificial intelligence, i.e., highly advanced logic, will never be able to handle something that it's not designed to handle. Human participation will therefore from a human perspective always be essential and automation is because of that forever constrained to be nothing but an assistant. This is here stated as the automation paradox, that regardless the capability of automation it will always require human guidance. Because, even the most advanced adaptive self-learning and artificially intelligent system will only be able to learn what it's been designed to learn. If mankind eventually succeeds with something that looks like breaking this paradox and manage to develop systems that are able to learn arbitrary things, including to develop its own ambitions and desires in order to make autonomous decisions, then perhaps the truly autonomous system is invented, and the inevitable question emerges: Is that what mankind actually wants? The paradox remains!

2.2.3.3 The Human Paradox

The automation paradox may be rephrased as that it's impossible to write rules for every possible situation, or even for every part of any situation. That means that there will always be situations, or parts of every

situation, where automation either will act ambiguously or according to an improper set of rules. On the contrary, a human being is able to apply the known set of rules in an arbitrary context and fill the gaps with what's best labelled as intuition, experience and common sense. One can always argue whether such a decision is the best or if an automated decision without any subjective feelings is better, but bearing in mind that life in general and military activity for certain is nothing but human beings interacting trying to influence each other, there is virtually no option. The topmost context is human life and it's only participating humans that are allowed to judge in that context. That is, decisions with adherent uncertainty affecting humans must ultimately be based on human judgement, which consists mostly of intuition. And it's equally illegitimate if technology autonomously makes these kinds of decisions or if it somehow reduces the human ability to make sensible judgements. The paradox then becomes that regardless of how subjective and irrational, i.e., how technologically lousy, human decisions are, they still are the only correct, valid and allowed ones at the highest levels of abstraction. When there are no or unclear predefined rules, when there is true uncertainty, life itself, which was stated as the topmost context, is humans acting on intuition, regardless of whether it's right or wrong.

2.2.3.4 The Principle of Uncertainty

It is by nature impossible to exactly predict the future, even in the shortest of terms. That is, every situation contains a certain amount of uncertainty, which here is defined as the concept of Situation Uncertainty (SU). Furthermore, every situation alters continuously, which has the consequence that uncertainty is self-generating. Uncertainty increases with amount of time in advance, probably exponentially.

Nearly everything in the every-day life in the civilian society is benign or well behaving, at least in theory. The situations contain natural damping. This is because everyone involved is supposed to want everything to work properly. The situations become self-regulating. It may be seen as a stable system. System shortcomings are avoided if possible and otherwise handled in an as good as possible manner. Which means that for a system that will work in 95% of every known case the probability of the other 5% to occur is reasonably low. On the other hand, all kinds of conflict situations, i.e., business situations and negotiations in general, but especially military situations are more like malignant or evil behaving. This is because there is at least one opponent that will do everything possible to exploit any kind of weakness. The situations become self-escalating. It may be seen as an unstable system. System shortcomings are particularly rewarding weaknesses that are searched for, and tend to be found and exploited by the opponent. Which means that for a system that will work in 95% of every known case the probability of the other 5% to occur is quite significant.

That is, conflict situations have greater probability for unfavourable situations to occur and greater probability for severe and escalating consequences of these situations. Hence, situation uncertainty is from the start greater in conflict situations compared to normal every-day-life situations, and furthermore, the uncertainty has most certainly a greater rate of increase as well. Therefore, automated solutions that work acceptably in civilian environments will not per se function properly in conflict situations.

However, although it's virtually impossible to completely eliminate situation uncertainty, it's definitely possible to constrain it and keep it under control by reducing the number of degrees of freedom. That is, the uncertainty is possible to grasp and handle if the situation is simple enough. In other words, uncertainty may possibly be under control if and only if the worst-case scenario is acceptable. The question to ask in order to find the situation uncertainty is then, how wrong can it possibly go? If there is uncertainty about what to do, the worst thing that can happen is that wrong thing is done. If there also is uncertainty about where to do it and when to do it, the worst thing that can happen is that wrong thing is done at the wrong place and at the wrong time, which probably is just about as bad as it could get!

2.2.3.5 The Principle of Control

It's a significant difference between to have control and to perform control. The state of having control may perhaps be the result of the work done by performing control, but it's not a necessary consequence.

For a human to be able to have control there must be awareness about the situation and about the entity to control together with a capability to control it. When it comes to controlling humans the capability to control may possibly be replaced with trust. Regarding technological systems trust is knowledge about and personal experience of the systems' capability to function both inside and outside its intended envelope. That is, trust for the systems' robustness. For a human being it's possible to have trust in that this person will act to the best of abilities, according to a common ground of values, even in unknown and complex situations. This includes the assurance that the human will break a commitment and do whatever's found to be necessary if the situation demands it.

Trust for a system is different. It will do what it always does, if possible, which sometimes is a quite reassuring behaviour – but it will do that even if the situation happens to require something else, unless the system actually is prepared to alter its performance, which then makes that kind of situation not really unknown. This is especially disturbing for uncertainties in the higher levels of control, uncertainties about what to do and why it has to be done. A systems preparation to alter its behaviour is commonly an implementation of a certain amount of rules, which then is to take a selected amount of abstract issues into account. Abstract issues are earlier stated to have the peculiarity that another rule may have the power to alter the present ones.

The overall capability to control consists of designed possibility and human ability to control. Human ability consists of awareness together with experience and skill. Humans tend to gain experience and skill while training for ability, which is done by actually utilizing the possibility to control. Furthermore, the situation awareness does profit from experience as well. That is, to have control the human is likely to require the experience of some hands on work of controlling, since that's what creates the ability that constitutes the capability that is required to actually have necessary control. This is probably a core foundation for the irony of automation. The challenge then becomes to design automation to perform tasks that relieves the human from workload in a way that it simultaneously keeps the human in the loop well enough to maintain control, which may appear to be contradictory. The key is here believed to be to carefully design the character of the interaction, the intensity, level of abstraction and capability of adaptation.

Levels of abstraction and levels of control are phrases that tend to be slightly deterministic. In such models the interaction or control tend to be viewed as being made at a certain level only, which is somewhat framing. The concept of "layers of control" might help in viewing this as concurrent or parallel processes. Control and interaction are performed at all levels, or in all layers, simultaneously. Automation within a layer of control may help a human and reduce the workload required to do that task, or even completely replace the human and do the entire work, but automation does always have design limitations when it comes to the capability to handle unpredicted inputs, which commonly is the outcome of some higher layer. The problem is to design the automation to avoid making it more difficult for the human to discover and add the new inputs to the matter and to tweak the performing of the task according to the new situation. Furthermore, if there is automation, as opposed to humans, that transfers the information between the layers as well, then the risk of doing the wrong thing at the wrong place and at the wrong time, described above in the section about uncertainty, is significantly increased. Therefore, the transfer between the layers need to take the entire context into account and follow the overall purpose even when additional and unforeseen parameters appears. It therefore needs to be controlled by humans. This becomes more important the higher the levels of control that are involved.

MILITARY RELEVANCE

Another way of maintaining control is to set boundaries, to state constraints. For instance, a completely automatic system that is uncontrollable when fired, but that has clear constraints and a robust behaviour may still be considered under control. The danger lies within the ambition to develop more flexible systems and the adherent design of more complicated constraints, which then may introduce uncertain behaviour in complex situations.

2.2.3.6 Designed and Applied Effect, Robustness, Versatility and Flexibility

A system has certain designed capabilities that possibly may give a designed effect, which is when it performs as it's supposed to do, in an environment (both physical and contextual) that it's supposed to have. Capability is the prerequisite for effect to occur, at all. One way of describing robustness is when the system still will perform even when the environment changes into something less favourable. Robustness is some built in assurance that things possibly will function even when the situation is starting to get tough. Versatility can be said to be when the system is capable of doing more things than what really is necessary. And, versatility together with robustness creates the potential for flexibility.

Flexibility however, requires the ability to adapt. Automation is able to adapt to what it's designed to adapt to, which creates what accordingly need to be labelled designed flexibility. True flexibility is then a strictly human quality. Together it forms a flexibility that may be applied among the uncertainties of reality, an applied flexibility.

Furthermore, the human's ability to change the context is also a source of creativity. Another viewpoint and unpredicted input may create opportunities to improvise and apply system capabilities in a way that gives a certain advantage in precisely that situation, to create an applied effect.

Automation capability is by definition part of the designed effect since it has the capabilities it's designed to have. To further illustrate the concept of applied effect, consider the following example: An ace operator is not the one that always performs as supposed to, facilitating the systems designed effect. The ace is the one that's able to take advantage of something unforeseen in a situation. This is obtained by being truly flexible and able to utilise system capabilities, sometimes in ways not intended when designed, which includes relying on robustness and exploring versatility. In this way it is possible to create an applied effect that may perhaps be applicable in that unique situation only. Designed effect is the necessary power to outbalance the armament race and applied effect is what wins the fight!

2.2.3.7 The Principle of Necessity – The Human Axiom

The Philosophy, the Principle of Uncertainty and the Principle of Control together indicates one obvious conclusion. There is really never a question of whether or not it should be a human involved in what a system does. The only relevant question is how the human should be involved and hence, yet another principle is defined. The Principle of Necessity, which then says that it's absolutely and unquestionably necessary that the human has control, that there is a human in charge. It is this unquestionable nature that makes the word axiom so compelling, it's just that's the way it is, it's fundamental.

Every reduction of human control over technology is by definition negative. If control, in defiance of that, is to be reduced, it must be completely justified.

2.2.4 Platform Characteristics

The perhaps more common phrase “unmanned aerial vehicles (UAVs)” is strictly speaking wrong. It's in reality nothing else then a separation of the human and the platform, which makes “uninhabited” a more

suitable word. Still, it's all about a separation that may be more or less complete and which implies different characteristics depending on the design of the system. Besides physical characteristics, where the inherent possibilities coming from not having a human onboard are the desired effect, separation states the prerequisites and creates the conditions, for control of the platform.

If an uninhabited platform is completely automatic, i.e., there are no means by which to control it after launch or after a certain point in time, a complete separation in time has taken place. The separation in space states that even if there is a communications link that makes it possible to somehow control the platform there will be a change in the character of control compared with not being separated. That is, separation is done in time and space and the consequence are a change in the character of control, which may vary over time.

It's the character of the platform that states the type. The difference between inhabited and uninhabited platforms is settled by a single parameter, which naturally is whether or not there is a human onboard. The difference between a missile and an UAV is not that simple. It could perhaps be determined by the use-once factor of a missile. Another possible identifier is that a UAV is more of a platform, it's the payload that does the work and it may perhaps be replaced. Compared with a missile, which is more or less entirely dedicated for its task. The character of the interaction may be used to state the difference between a remotely piloted vehicle (RPV) and a UAV, where the former is more directly controlled at a lower level of abstraction than the latter more highly automated kind of vehicle.

2.2.5 Interaction (Control) Characteristics

Separation in space of the human and the platform inherently creates a reduction of the extent of the interaction between them, a reduction that is dependent on the capability, i.e., bandwidth, of the control link. Even with an unlimited amount of bandwidth there will be a reduction in interaction, a reduction that is dependent on design. Due to the physical separation, the only possible interaction is what's designed to occur. That is, the system will only convey information that it's designed to convey and reality will always bring at least one more relevant piece of information to the situation. What have been lost are very often alternative kinds of feedback channels and especially all sorts of subtle, abstract and intuitive ones, which commonly are quite underrated.

Separation in time of the human and the platform is merely when the separation in space occurs. Since separation in space creates a change in the character of control the timing issue states when this change takes place. For completeness, the character of control may vary over time, but typically it's a question of a time-dependent reduction of the possibility to interact. Furthermore, it may come to a certain point in time when the possibility completely disappears, e.g., "fire and forget", and where situation uncertainty inevitably starts to self-generate. The character of control, in other words the possibility to interact, is a tool used to handle situation uncertainty. The informative part of the interaction, i.e., the feedback, is the base for reduction of uncertainty and the possibility to control is the means by which to act or react.

The characteristics of the control may be described with its stability, continuity and robustness and is very much dependent on the characteristics of the interaction. The characteristics of the interaction may be described with its intensity, level of abstraction and possibility of adaptation.

To summarise, the physical separation of operator and system puts constraints on the possibilities to interact with the system. Interaction is a major part of "The Principle of Control".

2.2.6 Relative Strengths

The relative strengths of uninhabited vehicles are almost without exceptions spawned out of the actual separation of the human and the platform. An obvious exception is the class of strengths that comes from the perhaps most common aim of automation itself, i.e., relief of strain, reduction of workload, which obviously is one of the main purposes for automation within inhabited (manned) systems.

The relative strengths are very well summarised with the well-known triplet – dirty, dull and dangerous – but these words need to be unfolded into something with more details. First it's possible to identify that there are direct and indirect strengths. The direct strengths may be sorted into the three classes of time, task and environment. The indirect ones are mutually dependent on each other, but could be described with cost, risk and importance (military and political).

Automation has no common human requirements for food, rest and convenience, which mean that many human time limits are possible to be ignored. Human limits in long time attention and physical exhaustion together with performance variances over time may be reduced as well.

Tasks may be unsuitable for humans in quite many ways. For instance, too demanding characteristics may be unsuitable, like the need for extremely quick response, e.g., unstable platforms. Or physical strength may be unsuitable, e.g., tasks requiring hydraulics. Too simple tasks – monotonous ones, or tasks that have nothing or little relevance for the overall situation – tend to make humans bored and perform poorly.

The environmental strengths are many and adjoin to the risk parameter. Every situation where humans would suffer or be unable to exist is in some sense a bad environment for a human being. This includes, for instance, very high or low pressure as in great depths, high altitudes or high acceleration forces, i.e., high Gs. It includes toxic environments as in N-B-C environments or extreme temperatures. Or it may be unsuitable size requirements, i.e., too small for humans to fit. Unhealthy environments are those that create a certain risk for a human if exposed to it and the most common military one is that of being opposed and perhaps fought down.

The indirect strengths are for instance, while being without the risk of human loss, having the possibility to take risks. However, there is always a cost committed to most things and advanced, capable and in reality useful systems tend to be quite expensive, with or without a human onboard. That is, it comes down to overall importance, like economical importance and political concern. An important matter may justify the risk of loosing expensive equipment. A political extremely sensitive matter might possibly even justify the risk of loosing human life.

These relative strengths are in certain situations so important that they may outweigh just about any weakness, if for no other reason just because there are no other options. The philosophy above doesn't in any way oppose this. It just points out that if the adherent weaknesses are well known, it might be possible with clever design to reduce their consequences.

2.2.7 Relative Weaknesses

Most weaknesses of uninhabited systems are consequences of loss of control depending on automation either forced by the separating design or by unsuccessful automation efforts that sometimes are driven by the technological hysteria, i.e., proofs of the irony of automation. Either or, it has something to do with automation and character of control, which certainly not is something reserved for uninhabited systems. These problems are undoubtedly present in manned systems as well – but the separation of the human and the uninhabited platform more or less forces extensive automation to be done, and this sometimes in areas with

less experience from actually using automation. That's why the problems tends to be at least one order of magnitude greater.

Modern conflict situations with great complexity and sensitivity quickly alter relevant parameters. Situation uncertainty is significant and quickly self-generating. Predictions, early decisions and logical rules that at one moment are correct and relevant quickly become obsolete. In such situations there is a severe risk that automation assumes or disregards something that is uniquely important and perhaps important at exactly that situation only. Furthermore, it's not unlikely that there will be rules of engagement (ROE) that for some reason, and sometimes unintentionally, will inhibit the use of such a system, which in turn will create undesired disadvantages.

These indirect weaknesses are connected with the indirect strengths as well. Loss of control due to automation is in itself a risk of doing wrong, which must be judged against the risk of doing nothing or against the risk when using humans, etc. The weaknesses are mainly lack of robustness in the higher contexts, which doesn't necessary need to be opposed with removal of automation. Lack of robustness due to automation problems is perhaps more the result of not addressing an issue than of addressing the issue wrongly. The unique human ability to apply every matter in a wider context makes handling uncertainties in the overall context very much a strictly human business. Automation should help humans handling such by always being designed to support human control as opposed to being a replacement for the human.

2.2.8 Summary and Relevance

Relative strengths follow quite directly from separation of human and platform. Relative weaknesses are mostly consequences of loss of human participation that more or less follows from the same separation. Strengths are direct results from technological design and are thus easily spotted. Weaknesses are indirect, sometimes abstract and often not recognised until tested in the dynamic environments of real situations with true and actual uncertainties that are context dependent.

Relevance of technological solutions, especially military ones that deliberately cause harm, needs to be judged thoroughly. In order to judge something, both strengths and weaknesses need to be known. Military effect is effect accomplished by military people, in modern times most commonly founded by technological systems. Relevant military systems are systems that complement the military people. Furthermore, identified technological strengths are easier to correctly exploit, will have better effect and will be more difficult to oppose if they are put into context, if their corresponding weaknesses are fully comprehended and where possible addressed. There is no military system more relevant than the one that actually wins the fight.

MILITARY RELEVANCE



Chapter 3 – THEORETICAL FRAMEWORKS

Chapter Lead: P. Farrell

**Contributors: P. Farrell, J. Gersh, E. Hollnagel,
I. MacLeod, C. Miller, A. Schulte, P. Stensson**

3.1 INTRODUCTION

3.1.1 Background

The NATO RTO Human Factors and Medicine Panel Task Group 017 entitled, “Uninhabited Military Vehicles (UMVs): The Human Factors of Augmenting the Force” involves studying ways to enhance military Forces by leveraging the potential advantages of UMVs to act as force multipliers. This report identifies, prioritizes, and addresses the Human Factors (HF) issues associated with integrating UMVs into the Force. Simply put, reducing operator-vehicle ratio and improving interoperability will augment the Force – both of these tenets require HF consideration.

Currently, up to six positions are involved in High Altitude Long Endurance (HALE) Uninhabited Aerial Vehicle (UAV) missions such as the Global Hawk. Medium Altitude Long Endurance (MALE) and Tactical UAVs have three positions operating them, such as the Predator B and SPERWER. Uninhabited Ground Vehicles (UGV) and other small UAVs have a one to one operator to vehicle ratio. It is anticipated that future uninhabited vehicles will operate as a team (or more commonly referred to as a swarm) with only a single human as part of the team [1]. One vehicle could detect targets, while another could act as a communications relay, and yet a third could target and track the target, and so on. Thus, the team of vehicles would augment the human’s own ability, and in turn augment the Force.

3.1.1.1 Reducing Operator to Vehicle Ratio

One HF consideration is the number of vehicles that a single human (or a crew) can operate. This issue, in part, is under investigation in Canada under the Intelligent Adaptive Interface programme [2,3,4]. It is related to human information processing considerations and involves human limits to perceiving information, working memory, goal setting, decision-making, and acting on those decisions.

3.1.1.1.1 Perception

For example, a UMV has the potential to provide persistent twenty-four hour surveillance of a stationary or moving target. A human operator may have access to hundreds of gigabytes of data, but is likely to ignore, shed, or chunk a large part of it. Automatic target recognition, directed attention algorithms, fusion algorithms, large database visualisation and intelligent search algorithms may help the operator in managing the data. Never-the-less, there is the potential to increase the data exponentially as more vehicles are added to the team.

3.1.1.1.2 Memory

Simplistically, a human limit to working memory is seven plus or minus two items [5]. For dynamic working memory, the number drops to two or possibly three items [6]. Thus, one might postulate that operators can

THEORETICAL FRAMEWORKS

actively control a maximum of two uninhabited vehicles. In a recent experiment, a crew of three was able to manage up to six UAVs towards completing the mission. We suspect active control of each vehicle is not possible, but other system architectures can be employed so that a single operator can manage multiple vehicles. For example, a single operator might control a single vehicle, which then controls all other vehicles on the team. Or a single operator might supervise and direct all the vehicles (similar to an air traffic controller). Or a single operator may act as a team player (maybe the team captain) in a collaborative team where most team members are machines. Regardless of the strategy employed, as one adds more UMVs to augment the Force, there is the potential to overload working memory.

3.1.1.1.3 *Goal Setting*

Goal setting becomes important for human-machine interaction, and even more critical for teamwork. Individual goals need not be the same, and in most cases must be managed by training or by a hierarchical structure of roles and responsibilities. It is important, however, that there is common intent amongst team members [7] – that is a common understanding of the goals, information needs, and actions to be taken in order to achieve the mission objective. Uninhabited vehicles that have the ability to dynamically set goals based on mission objectives, environmental conditions, or human psychological and physiological conditions (i.e., levels of automation/autonomy) could be treated as team members. Conceptually, all the team attributes would still apply in this human-machine interaction case, including goal setting.

3.1.1.1.4 *Decision Making*

Decision-making involves understanding the mission objectives and desired states, interpreting the current state of the world, developing possible actions/communications strategies, and choosing one of those strategies that will impact the world and move the current states closer to the desired states in an effective manner. At low levels of abstraction, cruise control and autopilots already sense the world, compare their sensory information to goal states, and make appropriate decisions and actions based on relatively simplistic rules and heuristics. At a certain level of abstraction, future intelligent and adaptive vehicles might make high-level (human-like) decisions. Vehicles may have the ability to make decisions about collision avoidance, target prosecution, and self-preservation. This raises many issues from goal de-confliction, to defining areas of responsibility and authority amongst the team members, through to legal, moral, and ethical considerations of machines making high-level decisions.

3.1.1.1.5 *Behaviour*

A human is limited to how many vehicles he or she can physically control simultaneously. There is an implicit assumption that the human would not physically manoeuvre multiple vehicles simultaneously, but that the operator would perform some form of waypoint navigation. Investigation is under way with two modes of operation. In the first case, the vehicles are treated as separate entities, and in the second case the vehicles are treated as a single entity (i.e., a swarm or team of vehicles). Automatic Pilots are sophisticated and mature enough in sea and air environments to manoeuvre in controlled air and sea spaces with minimal human assistance. However, in ground environments, artificial intelligent navigation still requires further development for the vehicles to transverse the complex terrain – indoors as well as outdoors [8].

Although augmenting an operator with multiple vehicles is the first objective, the system designer must be cognisant of human limits with respect to perception, cognition (goal setting, working memory, and decision-making), and action. Thus, this report looks at how to augment the Force by optimizing the operator/vehicle ratio while staying within human limits – this is indeed the Human Factors of Augmenting the Force.

3.1.1.2 Interoperability

The second objective is to augment the Force by improving interoperability. The concept is that multiple operators from different forces (e.g., multiple military services, multiple countries, other government agencies, and non-government agencies) can operate a single UMV. In some ways, this objective seems to conflict with the first objective since there is the potential for multiple humans controlling one UMV instead of one human controlling multiple UMVs.

Sharing assets can augment the Force. In a recent experiment off the east coast of Canada, the Air Force operated a MALE UAV while the Navy commanded the UAV and the sensor information was shared to all military services as well as other government agencies. A significant amount of coordination was required, but the asset and particularly its product were shared successfully. This concept requires technical standards at the level of machine design, and the coordination of competencies, authorities, and responsibilities at the level of command and control of all parties involved.

3.1.1.3 Research and Development Areas

The Task Group identified that augmenting the Force will require research and development in the following areas:

3.1.1.3.1 Collaborative Work – Optimal Task Distribution

- Virtual team performance
- Manned/Unmanned collaboration
- Interoperability
- Flexible level of automation
- Optimization of operator/vehicle ratio

3.1.1.3.2 Control Stations – Intelligent Operator Support

- Operator functional state assessment
- Intelligent adaptive interfaces
- Cognitive cooperation
- Knowledge management systems

3.1.1.3.3 R&D Areas Grouped into Five Thematic Areas

- Theoretical Frameworks
- Supervisory Control
- Advanced Interfaces
- Levels of Automation
- System of Systems

This chapter focuses on Theoretical Frameworks.

3.1.2 Why Theoretical Frameworks

Theoretical frameworks have been used to guide the design of technology, procedures, systems, and systems of systems. UMV systems will also require theoretical frameworks to inform the design process. Most of the frameworks used in traditional manned systems can be applied to uninhabited systems. However, revisiting the theoretical frameworks discussion allows us to highlight aspects of the frameworks that are directly applicable optimizing operator/vehicle ratios and interoperability of uninhabited systems. In the investigation we may also find an emerging theory or framework that is unique to UMV systems.

A framework encapsulates the design process that typically is built on theory or a model as well as practice. Three types of design processes (or frameworks) are systems engineering approaches such as described in [9] “build a little and test a little”, and arbitrary/creative design. The systems engineering approaches may produce optimal solutions, but are expensive both in time, energy, and money. “Build a little, test a little” incremental design approach may be cost effective, but it requires several design cycles to optimize. Arbitrary/creative design is often performed, but often at the expense of optimal system effectiveness.

The place for theory in design is as follows:

- Theory can be the starting point for design;
- Theory may identify the critical design decisions;
- Theory allows for a common taxonomy within and across systems;
- Theory helps track and maintain the aim throughout the system life cycle;
- Theory helps design system verification and validation; and
- Theory helps generate measures of effectiveness.

There are a number of theoretical frameworks that address operator/vehicle optimization and interoperability. Theoretical frameworks developed for operator-manned vehicle interaction can be applied to uninhabited systems when it comes to basic ergonomics, workstation design, task analysis, workload and situational awareness. In most cases, human-machine interaction theories apply regardless if humans are inside or outside of the vehicle, although ego- versus exo-centric frames of reference may become an issue specific to UMVs. Human-human interaction theories (i.e., social behaviour) might better describe operators who interact with vehicles as a team. Thus human-machine and human-human interaction theories are reasonable starting points for exploring operator/vehicle and interoperability optimization.

The choice of framework for analysing and designing UMV systems may depend on the proposed solution. For example, if reducing the operator/vehicle means going from three operators operating one vehicle to one operator operating three vehicles, then one can imagine the requirement for intelligent help and levels of automation. The theoretical framework will need to address the following aspects:

- Level of automation and time and cultural dependencies.
- Goal/constraint level interactions instead of action level interactions.
- Self-generating future plans.
- Environment and system unpredictability.
- Trust and system acceptability and predictability.
- Implications of truly autonomous (free will) systems.

- Animation and personification of machines.
- Self-awareness, environment awareness, and awareness of itself within its environment.

While the theory may be the starting point of the design, aspects of the design define the theoretical framework to be applied. There is some initial iteration and recursion in determining the theoretical framework, however this recursion should quickly converge so that the design can move forward.

3.1.3 Scope of Theoretical Frameworks Theme

At the present, no single theoretical model can be argued to encompass all aspects of human and systems work and performance. However, theoretical frameworks help us focus on what we do know about systems and illuminate what we yet need to discover. These frameworks should lead to an assessment of the effectiveness of UUV systems in augmenting the force. As a start, workshop participants proposed three framework categories.

3.1.3.1 Human Performance Models

- Human in control (hands-on, supervisory, collaborative)
- Human problem solving
- Human information processing
- Time and motion
- Human attention demand

3.1.3.2 Humans as Part of a System Models

- System Engineering
- Process/Task
- Team working
- Organisational Behaviour
- Joint Cognitive System

3.1.3.3 Human Cognition Models

- Mental processes
- Memory
- Personality and Motivation
- Interoperability (team dynamics, communications, politics, culture, and organisational issues within a coalition of diverse forces, and the human within system of systems)

3.1.4 Identifying Relevant Theoretical Frameworks

A literature review was conducted as a first attempt to capture relevant theoretical frameworks. Ten out of 127 papers were found that were deemed highly relevant to this topic – particularly the human-machine

THEORETICAL FRAMEWORKS

interface. Complete descriptions are found in Appendix 3-1. Synopses of seven of these papers are found in the next section. Naturally, these papers did not address directly the objectives of reducing the operator-vehicle ratio and optimising interoperability. Thus, we asked selected authors to comment directly on the relationship between their theoretical framework and the objectives.

Two options were discussed at the Leiden Workshop that could help streamline and focus the investigation of theoretical frameworks. The first option was to evaluate frameworks against a common military scenario (see the scenario section, Chapter 2, para 2.1.6). However, if there is a significant mismatch between theory and operation realities then the comparison may be invalid. That is, elements of theoretical framework must be related to elements of military operations. Also, deciding on the rules for adopting frameworks would be a formidable task.

The second option (the option we adopted) was to take a closer look at six frameworks and ask how would they address operator-vehicle ratio and interoperability directly. The frameworks could be compared to standard systems design approaches and to each other. In order to converge onto a core set of theoretical frameworks, we solicited comments from selected authors and asked them to discuss their theory or model specifically in terms of optimising the operator-vehicle ratio and interoperability. This option is limited by this Task Group's limited knowledge and reach in the member nations, although an effort was made to be as thorough as possible.

At the Leiden Workshop, key programs and individuals who contribute to UMV human factors from NATO countries were identified. Table 3-1 provides the survey questions, which were developed directly from the Terms of Reference for this Task Group. The survey was sent to 10 individuals, and 6 surveys were returned. Their responses are found in Appendices 2 through 7.

Table 3-1: Survey Questions

<p>Force Multiplication</p> <ul style="list-style-type: none"> Does the framework/model address operator to UMV ratio issues? <ul style="list-style-type: none"> If so, how could the framework/model help reduce the ratio? Does the framework/model address interoperability issues? <ul style="list-style-type: none"> If so, how could the framework/model help improve interoperability?
<p>UMV Scenarios/Use-Cases</p> <ul style="list-style-type: none"> Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?
<p>Theory Evaluation</p> <ul style="list-style-type: none"> Has the framework/model been evaluated, tested, and applied to commercial or military operations? Do you have an example, closely related to the UMV situations, where the theory was implemented?

3.2 FRAMEWORK DESCRIPTIONS

3.2.1 Literature Review

A literature survey was commissioned to assess the scope (breath and depth) of the literature related to operator-agent interaction for intelligent adaptive interface design. The actual searching fields were beyond suggested areas such as tele-robotics and human computer interaction, and included supervisory control, information management and decision support, automatic manufacturing, medical diagnosis and consultation, and other social behaviour areas. More than 500 abstracts were retrieved, 127 papers and reports were found likely relevant to the research domain, and 82 were reviewed of which 27 dealt with theoretical models and empirical evaluations. A detailed review was made for seven of those papers and these brief summaries are listed below.

3.2.1.1 Models for the Design of Human Interaction with Complex Dynamic Systems (Systems Engineering & Management Handbook, 1999) by Mitchell, C.M. (1996)

This paper provides an overview of the evolution of human-machine systems models over the past forty years. From perspectives of cognitive engineering, ecological psychology, and naturalistic decision-making, the similarities between human-machine systems models and a variety of other recent approaches to understanding and aiding human interaction in real-world systems were described. The paper also proposed a set of tenets that characterizes models and human interfaces whose design was based upon the models.

The paper described the trend of developing robust models with the same levels of fidelity as system models. The vision was to predict both system and human behaviour and provide quantitative assessments of the proposed system design. In 60's and 70's, the crossover control model and the optimal control model (Wickens, 1984) focused on continuously tracking behaviour for fully manual tasks. However, with Digital Computer introduced, tasks are supervisory controlling of multiple subsystems. Since then, modelling objectives changed from the pursuit of a global and analytic/computational operator simulation (i.e., a quantitative, predictive model) to a more focused development of system and task representations that could be used for the design of operator interfaces to complex dynamic systems, including displays, aids, and training systems. Therefore, the objective was no longer to produce a black-box human operator simulator that functions as robustly as traditional engineering models of system hardware and software, but rather the development of a useful description/prescription of the system-task-operator interactions. Understanding and modeling human cognition, problem solving, and decision-making became more and more popular and practical for the system design.

The essence of this paper is the emphasis of the importance of context as the central tenet of Human-Machine Systems Engineering. As Baron (1984) summarized this requirement succinctly: "[A human-machine systems model] ... embodies the idea that to model human performance, one must model the system in which that performance is embedded." Human behaviour, either cognitive or psychomotor, is too diverse to model unless it is sufficiently constrained by the situation or environment; however, when these environmental constraints exist, to model behaviour adequately, one must include a model for that environment (the perspective of ecological interface design). Therefore, the system design should be context-oriented, descriptive, and prescriptive.

THEORETICAL FRAMEWORKS

3.2.1.2 A Theoretical Analysis and Preliminary Investigation of Dynamically Adaptive Interfaces (Journal of Aviation Psychology, 11(2), 169-195, Copyright © 2001) by Bennett, K.B., et al. (2001)

This paper described a dynamically adaptive interface (DAI), which changes display or control characteristics of a system (or both) in real time. The goal of this DAI is to anticipate informational needs for desires of the users and provide that information without the requirement of an explicit control input by the user. This research found that DAIs have the potential to improve overall human-machine system performance if they are properly designed. However, DAIs also have a very real potential to degrade performance if they not properly designed. This study explores both theoretical and practical issues in the design of DAIs. The relation of the DAI concept to decision aiding and automation was discussed, and a theoretical framework for design was also outlined. This paper shows that one can apply theory to design!

In this paper, a preliminary investigation of the DAI design concept was conducted in the domain of aviation (precision, low-level navigation). Three interfaces were evaluated including: non-traditional controls (a force reflecting stick) and displays (a configurable flight director) were developed to support performance at the task; a standard interfaces (conventional controls and displays), a candidate interface (alternative controls and displays); and an adaptive interface (dynamically between the standard and candidate displays). The results indicated that significant performance advantages in the quality of route navigation were obtained with the candidate and adaptive interfaces relative to the standard interface; no significant differences between the candidate and adaptive interfaces were obtained. The implication of these results was discussed, with special emphasis on their relation to fundamental challenges that must be met for the DAI concept to be a viable design alternative.

This paper is a good example for human-machine interaction from theoretical development to empirical investigation to maximize overall performance. The design and comparison of three interfaces is a typical method for such kind of research. The results are also very interesting as they raised the issue of the dilemma for automation and adaptation. When, where, what, why, how to adapt is really a question theoretically and practically for better operator-machine, operator-agent interaction. The theoretical framework and research methodology are very useful for other similar research.

3.2.1.3 Integrating Perceptual and Cognitive Modeling for Adaptive and Intelligent Human-Computer Interaction (Proceedings of the IEEE Volume 90, Issue 7, July 2002, Page(s):1272-1289) by Duric, Z., et al. (2002)

Through both theoretical analysis and empirical investigations, this paper used human cognitive, perceptual, motor, and affective factors to adapt the interface design for intelligent human-computer interaction. The essence of the paper was to monitor affective behaviour or emotional behaviour or non-verbal information to answer what why, where, when, and how, and then adapt the display according to this information. The method for interface design is more human-like in which the interface/machine or the agent/automation embedded is regarded as another human assistant who can monitor perceptual and cognitive levels and understand the “partner” or “teammate”, thus react for better collaboration with better overall results. The idea was to emphasise the team collaboration that benefits human-human interaction. “It is not only computer technology that needs to change to make such novel interfaces a reality. People have to change as well and adapt to the interface that the computer presents them with. In the end, both people and the computer have to understand each other’s intentions and/or motivations, provide feedback to each other as necessary, and eventually adapt to each other.”

3.2.1.4 Adaptive Interfaces for Human-Computer Interaction: A Colourful Spectrum of Present and Future Options
(Proceedings of the IEEE 1995, 292-297)
by Lajos, B. (1995)

This paper discussed adaptations that could be built into interfaces for human-computer interaction based on different aspects of human behaviour such as physiological attributes (eye, ears, fingers, etc.), intellectual characteristics (capacity, recognition, learning, decision, etc.), knowledge basis (knowing the environment, the system, him/herself, etc.) and psychological states (concentration, vigilance, fatigue, patience, etc.). As pointed out in the paper, that adaptive interfaces should be capable of adjusting to different forms of information transfer, transforming the information contents, altering/merging modes of information flow, and exchanging/combining communication media.

The paper also discussed the future of adaptive interfaces, the role of formal interaction modeling, the importance of abstract/structural interface hierarchy, the integration of interaction modes and media, the sophistication of interface modularity and the exploitation of the advantages in combining/integrating conceptual-functional-physical design aspects. It is a good reference for the taxonomy of adaptive interfaces.

3.2.1.5 The Future of Watchstation Design: Evolution from Single Purpose to Intelligent Watchstations
(2002 Command and Control Research and Technology Symposium,
Naval Postgraduate School, Monterey, California, 11-13 June 2002)
by O'Donnell, L. (2002)

The focus of this paper is to address the issues in interface design and the changes in the console design to support distributed mission task activities for joint operations of global command and control systems. Increased mission demands combined with smart weapons, automated functions and increased collaborative warfighter functions have increased the multi-tasking requirements to be accomplished. Humans in a warfighter role have shifted from a narrow task focus within a narrow job focus of a single purpose watchstation and a high human-in-the loop interface workload, to becoming controllers of these distributed systems and collaborative activities. In the paper, current watchstation design was described that requires the human to perform manual system operations in combination with numerous independent synchronous activities such as communications and adjacent equipment operations. Future watchstation will need to be designed to support the work environment with: increased multi-tasking capabilities, dynamic monitoring of task process, integrated system designs, and improved distributed team collaboration task capabilities. Advances in technology have enabled the design of an effective watchstation design that will allow for multi-modal user interfaces best suited to the task. Future watchstation designs should also utilize self-adaptive interfaces, increased visual workspaces, agent technologies, integrated speech, and visual and direct touch methods to reduce the human-interface workload and streamline the tasks. All these features are required for future UAV/UCAV control interfaces.

The paper not only analyzed the current trends and advantages of intelligent interfaces (watchstations), but also brought up a smart agent taxonomy to construct the flexible, dynamic, scalable, and robust distributed system capabilities over system networks as multiple agent systems. Although the context discussed in the paper was not focused on airborne multiple UAV control, but the discussions of several key technologies to enabling an intelligent system and future research recommendations on intelligent user interface design can be generally applied to any design of the framework for optimal operator – agent interaction.

THEORETICAL FRAMEWORKS

3.2.1.6 An Architecture for Intelligent Interfaces: Outline of an Approach to Supporting Operators of Complex Systems (Human Computer Interactions, 3(2), 87-122)

by Rouse, W.B., Geddes, N.D. and Curry, R.E. (1997-1998)

This paper described a concept of a comprehensive support system design for operators of complex systems. A variety of difficult design issues were addressed as well as ongoing efforts aimed at resolving these issues.

The main focus of the paper was to address design methodology and automation philosophies. Although the suggested design methodology follows the traditional human factors engineering principles, automation philosophy emphasises on maximizing overall performance by overcoming human limitations and enhancing human abilities. The philosophy is that automation should be used as a backup – the default modes are usually manual with automation invoked only when either anticipated operator performance is unacceptable or the operator chooses to relinquish control. With the adoption of this operator-centred automation philosophy, an architecture including intelligent management of information and tasks was proposed. Within it, the concept of operator state is central to the functioning of the components of the intelligent interface. The relevant elements include: activities, awareness, intentions, resources, performance. Another component is the interface manager, which is similar to an executive's assistant who zealously guards the superiors' time and resources. Although important questions were raised about what, when, and how to automate, there was no clear answer in the paper. The paper presented a layout of the architecture for complex system design, but it did not cover enough cognitive and perceptual aspects of a dynamic, complex, and interactive system, especially for multiple UMV control.

3.2.1.7 A Model for Types and Levels of Human Interaction with Automation (IEEE Transactions on Systems, Man and Cybernetics, 30 (3), 286-297)

by Parasuraman, R., Sheridan, T.B. and Wickens, C.D. (2000)

A framework/model was proposed for types and levels of human interaction with automation (Sheridan's 10 points scale). They also proposed four broad classes of functions which automation could be applied from information processing point of view: a) information acquisition, b) information analysis, c) decision and action selection, and d) action implementation. Within each of these types, automation can be applied across a continuum of levels from low to high, from fully manual to fully automatic. A particular system can involve automation of all four types at different levels. Since automation does not merely supplant but changes human activity and can impose new coordination demands on the operator, appropriate selection is important based on the primary and secondary evaluative criteria. The primary criteria look at human performance consequences: mental workload, situation awareness, complacency, and skill degradation. The second criteria include the automation reliability and the costs of consequences.

Although the paper considered human machine interaction mainly from information process point of view, the proposed model could be a good starting point for considering what types and levels of automation should be implemented in a particular system. The paper is concerned with human performance in automated systems and emphasizes human-machine comparison. Automation is defined as a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator. The paper also touched a little bit on action automation – agents which track user interaction with a computer and execute certain sub-tasks automatically in a contextually-appropriate manner. However, this area should be elaborated more associated the theory developments and empirical investigations (which is the future work as mentioned in the paper). Even in the proposed model, the issue in whether automation unreliability has similar negative effects for all four stages of automation needs further examination. Regarding costs of decision/action outcomes, individual differences between users in the same interface

should be addressed more, especially on user profile building on the interface (user modelling embedded in interface). It is good to point out that empirical work needs to be done to explicitly compare the effects on human performance of different levels of automation for information acquisition and analysis, in other words, the levels of interface intelligence. Overall, this paper emphasised more function allocation between user and machine regarding automation, but less was discussed on operator interface interaction. How the automation should perceive, analyze, understand, react, and collaborate with user as an agent or assistant still remains untouched.

3.2.2 Frameworks from Survey Returns

The following framework descriptions were those of the six authors who responded to the survey. They serve as the main frameworks from which we can find any common or unique theoretical elements required to analyse UGV systems.

3.2.2.1 Cognitive Automation (CA)

Cognitive Automation makes a distinction between conventional automation and cognitive automation [10]. Also see chapter 5 for a full description of the theory. Conventional automation is predominantly focused on subgoals and subtasks of the work process. High-level goals and their associated tasks are not known by the automation system. Consequently, these systems observe only a small portion of what is relevant in a given situation. For example, if the “altitude hold” autopilot is activated, it is doing its best to comply with this assigned reference or goal state, even if a high mountain is in its way. The autopilot does not know, nor care about the top-level safety goal of avoiding a crash into the mountain – this goal is exclusively in the realm of the high-level operating element responsibilities (usually human supplemented by a machine). Never the less, conventional automation is very convenient for simple automated functions where the supervisor has direct visibility and influence on the states that the automation has control over.

Cognitive automation takes into consideration these high-level goals. The authors present the idea of an Artificial Cognitive Unit (ACU) that implements a model of the Cognitive Process, and the ACU has been coded in software. The ACU includes processing steps of interpretation ending up with beliefs, goal determination, planning, and plan realisation to generate the instructions for action. These processing steps are based upon a priori knowledge.

ACUs have the potential to achieve high-level goals compliant with those of the human operator, and therefore may act as an operator assistant system as well as act autonomously. Then, a “cognitive” autopilot will take into consideration the mountain in front, will know that to proceed stubbornly with altitude hold will end in disaster and it will look for a way around all based upon the high-level goal for safe flight.

3.2.2.2 Extended Control Model (ECOM)

The Extended Control Model (ECOM) has been described in a conference paper [11] and a book chapter in a textbook [12]. The pedigree of the model includes the description of the principle of contextual control [13], the initial contextual control model [14], and the fully developed contextual control model [15]. Also see chapter 7 for a full description of the theory.

Briefly explained, the model provides a framework for describing how a joint cognitive system can maintain control of a situation or a process. A cognitive system is defined as “a system that can modify its behaviour on the basis of past experience so as to achieve specific antientropic ends.” A joint cognitive system can be any combination of humans and machines (technological artifacts) or humans and humans (social groups/

THEORETICAL FRAMEWORKS

organisations). The model invokes the principle of multiple, simultaneous layers of control. The layers are hierarchically organised with one or more instances at each layer. Control layers differ with respect to the time window or time horizon they cover, as well as in the balance between feedback and feedforward control. The model currently describes four layers of control called (from the top down) targeting, monitoring, regulating, and tracking. It is applicable both to single systems (e.g., a driver and a vehicle) and to larger entities and organizations.

3.2.2.3 Multiple Agent Interaction (MAI) Model

A framework is proposed based on Perceptual Control Theory (PCT) [16] to model multiple non-interacting and interacting agents [17]. Agents, in this case, may be human or software agents that mimic human cognition and behaviour. This modelling activity was performed in order to understand the system dynamics of human-intelligent agent interaction, which would lead to design implications. PCT describes human cognition as a means-end hierarchical network of control units. Each control unit involves the control of a perception. At the lowest levels, control is subconscious and might be described by classical linear control theory. At the highest levels, control is conscious and deliberate requiring rule-based thinking, logic, and reasoning. Regardless of the hierarchical level, the control law remains the same – the output of each control loop attempts to drive the perception closer to its internal goal. The key advantage of modelling agents using PCT is that one can apply all the mathematical power of control theory including stability and optimization analyses.

From a control theory perspective, human-machine interaction is often analysed by treating the machine as a simple input-output transfer function with some known disturbances, and the human is part of the machine's controller algorithm [18]. On the other hand, multiple agent interaction should be treated as separate control loops that have independent reference values, and that interact only through the influencing and sensing of common states of the physical world. Conceptually, this interaction model would produce a complex set of dynamics that are not always stable and not easily predictable. Thus, as the operator-vehicle ratio is reduced by adding more intelligent agents, there is a risk of producing an unstable system if not carefully designed.

The following principles were highlighted during the analysis of multiple agent interaction using control theory techniques:

- Closed-loop feedback modelling techniques can be used in the design of multiple agent systems.
- Designers should consider goals, sensing and decision-making strategies, and world states as part of their system design.
- Agents should act on separate states, while gathering data from all sources.

These design principles have been applied to UMV research studies on the design of intelligent adaptive interfaces, and selecting crews for UAV operations. The third design philosophy was applied to information management business rules for the Multi-National Experiment 4 on Effects Based Operations with US Joint Forces Command as the experiment lead. This experiment involved over one hundred players over a distributed network from countries around the world. The interface design and business rules were critical in order to successfully collaborate and conduct the experimental operation.

3.2.2.4 Military Relevance Philosophy (MRP)

See Chapter 2 for a full description of the theory. The human axiom is to facilitate the development of technology and the use of it to actually serve the human in the best possible way. With respect to UMVs, the human axiom is to put the technologies of automation and uninhabited systems into a necessary context in

order to reduce the risk of having these capabilities become counterproductive. This is especially important when it comes to highly automated and uninhabited systems. Military effect is nothing but humans influencing other humans using military powers, commonly facilitated by technological systems. The axiom is to state that if there is no military human completely in charge of the systems' effect, then the effect isn't actually military and thus has no military relevance.

By nature, it is impossible to exactly predict the future since every situation contains a certain amount of uncertainty, which here is defined as the concept of Situation Uncertainty (SU). Furthermore, every situation changes continuously, and increases with amount of time before an event. Having control or being in control of situations with very high uncertainty is difficult. It is a significant difference between to have control and to perform control. The state of having control is a possible result of the work done by performing control, but it is not a necessary consequence of control (that is, even though control has been applied a system may diverge because of high uncertainty). To be able to have control there must be awareness about the situation (i.e., reduced uncertainty), the entity's ability to control its environment, and the control of the entity itself.

When it comes to "controlling humans", the concept of trust may replace the concept of control, because interacting entities are autonomous, self-aware agents. Humans deal with uncertain and complex situations trusting that the other human team member will act according to common values. One can imagine that trust will play a significant role amongst human operators and autonomous UUV systems. Humans may grow to trust the machine, but trust must be mutual under uncertain situations. The technological system must not only trust the human, but also itself particularly when the system functions outside its design envelope (i.e., SU). This is especially true for uncertainties in the higher levels of control, uncertainties about what to do and why it has to be done, and less true when it comes to uncertainties about how to do things. Current technologies do not have the capability to trust as defined herein.

Which results in the human axiom:

"Every reduction of human control over technology is negative. If control, in defiance of that, is to be reduced it must be completely justified. Reduction of control may be justified if and only if the worst possible consequences of the reduced control are exceeded by the benefits of reducing the control (Patrik Stenstrom)."

Relative strengths (i.e., safety and force multiplication) follow directly from separation of human and platform. Relative weaknesses are mostly consequences of reduced control because of the same separation as well as the lack of mutual trust. Relevance of technological solutions, especially military ones that might deliberately cause harm, needs to be judged thoroughly.

3.2.2.5 Playbook (PB)

As Unmanned Military Vehicles become more intelligent and capable, and as there is an attempt to control more of them with fewer humans in the loop, there is a need to move toward a model of delegation of control rather than the direct control that characterizes current practice [19]. Also see Chapter 7 for a full description of the theory. Five delegation methods are identified and described, and can serve as building blocks from which to compose complex and sensitive delegation systems: delegation through:

- 1) Providing goals;
- 2) Providing full or partial plans;
- 3) Providing negative constraints;

THEORETICAL FRAMEWORKS

- 4) Providing positive constraints or stipulations; and
- 5) Providing priorities or value statements in the form of a policy.

The Playbook architecture supports delegation action types 1 – 4 in principle and has been implemented in prior prototypes to include action types 2 and 4. While the work described above represents a general framework for delegation interactions suitable for human interaction with smart automation of various kinds and, perhaps uniquely, suitable for the tasking of multiple UMVs, the work has thus far progressed only to the proof of concept stage. The Playbook ‘proper’ consists of a User Interface (UI) and a constraint propagation planner known as the Mission Analysis Component (MAC) that communicate with each other and with the operator via a Shared Task Model. The operator communicates instructions in the form of desired goals, tasks, partial plans or constraints, via the UI, using the task structures of the shared task model. The MAC is an automated planning system that understands these instructions and (a) evaluates them for feasibility and/or (b) expands them to produce fully executable plans. The MAC may draw on special purpose planning tools (e.g., an optimizing path planner) to perform these functions, wrapping them in its task-sensitive environment. Outside of the tasking interface, but essential to its use, are two additional components. An Event Handling component, itself a reactive planning system capable of making momentary adjustments during execution, takes plans from the Playbook. These instructions are sent to control algorithms that actually effect behaviors.

The final type of delegation interaction offers the ability to provide priorities between alternate goals and states and to do so more abstractly than the above methods. These abstract value statements that a supervisor might provide are referred to as his or her “policy” for performance in the domain. A policy statement is an abstract, general, a priori statement of the relative importance or value of a goal state in the domain. In its simplest form, policy provides a method for human operators to mathematically define what constitutes “goodness.”

The work described above represents a general framework for delegation interactions suitable for human interaction with smart automation of various kinds. This work is in the proof of concept stage although exploration of Playbook-like interfaces is being conducted (under a DARPA-IXO SBIR grant). One of the goals of this work will be to develop task libraries and task construction tools and interface concepts to move the delegation interface work along toward implementation and utility.

3.2.2.6 System Process/Task Organisational Model for HF V&V (SPTO)

If “The Human Factors of Augmenting the Force” is indeed the objective then the outcomes produced should have enough practicality to consider their applicability in augmenting force effectiveness in the ‘real’ world. Amongst other considerations, it is important to consider the verification and validation (V&V) of a theoretical framework for augmenting the force. V&V is made both statically (verification) and dynamically (validation) – statically to ensure that it is basically logical and fit for intended purpose, dynamically to examine its fit to reality [20].

The System Process/Task Organisational Model for HF V&V presented at Leiden was shown using an embedded Theoretical Framework of Task Organisation. In the author’s view that framework always implies levels of consideration on Task Context, Situation, Mission, Goal(s) [possibly both Strategic and Tactical], Force Structure, Organisations, Cultural influences, the role(s) of technology, required system functions and performance, roles of personnel, jobs, teamwork, individual tasks, and individual actor / entity properties and activities.

If a system is considered dynamically it is with a task related perspective; if statically it is more at a function, constraint, architecture, capability, or generic process perspective of consideration. However, the model is

seldom expressed explicitly. The model relies on checks on the effectiveness of the progress of a system through its set process phases (i.e., What has occurred and When by forms of Measures of Effectiveness [MOEs]). To provide explanation of the quality of work performance throughout the phases of the process an associated Task Organisational Model provides evidence of the quality of work performance to satisfy questions on How, Why, Where, and by Whom task effort has been applied in support of the satisfaction of the goals of the system process (here possibly by the use of forms of Measures of Performance as associated with MOEs).

If proof is required that the application of HF to UMV life cycle issues will augment the force then it is necessary to provide a theoretical model with associated measures that if applied in practice can produce evidence of the degree that the application of HF has succeeded in its aim. One such model has been proposed. It is suggested that regardless of the form or efficacy of HF practices applied to the life cycle issues of employment of UMGs in a force, that the adoption of some form of a System Process/Task Organisational Model is necessary to fully evaluate a system, its capability, and its quality of fitness for purpose.

3.3 SURVEY RESULTS

The following table summarizes the survey results. For brevity, key sentences and/or phrases are taken from the responses in Appendices 1 through 7. For more detail please refer to the Appendices.

THEORETICAL FRAMEWORKS

Table 3-2: Survey Results

Question	CA	ECOM	MAI	MRP	PB	SPTO
Does the framework/model address operator to UMV ratio issues?	Yes.	Yes.	Yes.	No.	Yes.	Yes.
If so, how could the framework/model help reduce the ratio?	Will supplement human teams and thus affect operator to UMV ratio.	Enables a constructive discussion of allocations.	Has the potential to show optimal trajectories through the state space as the ratio is reduced.	Will help in <i>increasing</i> the operator to UMV ratio instead of reducing it.	Permits a single operator to do everything from joystick control to swarm control of any number of UAVs.	Considers automation, autonomy, manning, and personnel.
Does the framework/model address interoperability issues?	Yes.	Yes, Indirectly.	Yes.	Yes.	Yes.	Yes.
If so, how could the framework/model help improve interoperability?	Will handle problems covering the full scope of interoperability levels – both high and low.	Give guidelines about which information is needed.	Standards might ensure proper sensing of information, and action must be coordinated to ensure de-confliction.	Appropriate human control is necessary to achieve interoperability.	PB achieves interoperability by building the knowledge about how to utilize different resources into PB's Planner.	Task organizational model can be developed to consider interoperability.
Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?	Yes.	Yes (implied).	Yes.	Yes.	Yes (implied).	Yes, Indirectly.
Has the framework/model been evaluated, tested, and applied to commercial or military operations?	Yes.	Yes.	Yes.	Not applicable.	Yes.	Yes, Implicitly.
Do you have an example, closely related to the UMV situations, where the theory was implemented?	COSY flight. COSA. Mini-UAV field demonstration. Manned-unmanned teaming.	Automobiles. Nuclear Power plant. Closely related UMV example.	Multiple UAV interface design.	Not Applicable.	DARPA UAV project, PVACS.	No, only coalition operations.

3.4 DISCUSSION

3.4.1 Operator to UMV Ratio

Five out of six authors indicated that their framework would contribute to reducing the operator-vehicle ratio. This was to be expected since the authors were invited to comment. All but MRP indicated how this would be accomplished, or at the very least, how various operator-vehicle configurations could be analysed.

CA suggested that the Artificial Cognitive Unit could perform some high-level cognitive tasks that would be otherwise done by the human, thus freeing the operator to manage multiple UMVs. ECOM provides a theoretical basis to discuss levels of control and control allocation. MAI would caution that the real issue is not the ratio of operators to vehicles, but that the addition of (human or machine) intelligent agents increases the chances for instabilities. MRP would argue that if humans are to remain in control, then the ratio should be increased rather than reduced. Given that the operator is the “coach” and the UMVs are “players” then PB would claim that there could be any number of UMVs that adhere to the playbook. SPTO says that automation and manning should be considered in parallel.

In general, frameworks provide a common lexicon and/or analogy around which any specific configuration may be described and compared to other configurations. Some type of framework or model is required to predict performance when the operator-vehicle ratio is reduced. Without this modeling investigation, it becomes increasingly difficult to have confidence that the system will work.

3.4.2 Interoperability

Contributors inferred that their framework addresses interoperability, although there is some suggestion that interoperability was interpreted differently amongst the theories. In all cases, human interoperability at the highest level of abstraction was included in the interpretation. CA claims to cover the full scope of interoperability. ECOM would provide guidelines for the information needs. MAI would produce standards for information exchange between agents. MRP focused on human control as the means of achieving interoperability. PB has a Planner that includes the use of resources. SPTO may require some modifications so that the model addresses interoperability.

3.4.3 Applications and UMV Situations

The survey provided three questions on theory applicability, theory application, and specific UMV situations. The intent was not to exclude a theory because it had not been applied to a UMV situation, yet weight those theories that have been applied to UMV situations highly. All theories are applicable to UMV situations according to the respondents. Five out of six frameworks have been tested and applied to commercial or military operations. MRP is a philosophy and is strictly applicable to these questions. From the list of UMV situations, CA, ECOM, and PB seemed to be the most mature followed by MAI. SPTO has been applied to coalition operations, and MRP, again, is not applicable.

Like any application of theory there are compromises usually between cost, effort, and time. The final design is usually a “healthy” compromise between the theory and practical considerations. The key point here is that frameworks have gone from theory to implementation with positive and useful results.

3.4.4 Common and Unique Framework Elements

This section provides a first look at some of the elements that all the frameworks have in common, and then highlights some of the unique framework elements. The first common element is the notion of control theory. That is, most theories have the notion of desired states and actual states in conjunction with sensing the world and influencing world states. This seems to be true for animate or inanimate actors within the environment.

Another common element is the idea of a hierarchy. There is an admission that the framework should be able to cope with multiple levels of abstraction – from data sensing and perception through to higher goal setting, reasoning, and decision-making. If the model is a single level abstraction, then it is might not be able to address operator-UMV interaction.

A third common element is that most frameworks advocate the need for the actor to sense the world (environment), sense its own state, sense the state of other actors within its immediate environment (including the team lead), and understand the mission objectives. Effectively, the algorithm(s) must at least mimic to some extent human cognition what humans seem to naturally do when working in a team of humans (see Chapter 7).

Descriptive analyses are another common element amongst most frameworks. That is, investigation of operator-vehicle ratio or interoperability is done primarily by logically reasoning through the topics using the theory as a frame of reference. Some of the more mature theories have shown the instantiation of their framework in a product or by modelling and simulation to show that the concepts indeed work.

A final common element is that the theory often leads to design philosophy and guidelines. In the case of MRP and SPTO, the design considerations begin with philosophical statements. It becomes difficult to separate the model from the model's underpinning philosophy and perhaps it is not necessary to make this distinction. Only that a practical output of theory and philosophy are design guidelines.

One of the unique framework elements includes PB with the notion of a playbook. This is not precisely rule-based decision-making, nor is it free play. It does pre-suppose cooperative actors working together to achieve a common objective. Not every actor knows precisely what the other actor is doing, but at least their actions are consistent and they are moving toward a common goal. This uniqueness has tremendous potential for an operator managing multiple UMVs.

Another unique framework element is the mathematical analysis of MAI. That is, symbolic mathematics was used to draw conclusions from the framework. On the other hand, the assumptions that were applied to make the mathematics tractable could be easily argued that the resultant model does not reflect the true situation. Never the less, experimental results have shown that the theory has some validity and that the mathematics is only an alternative to descriptive analyses to come to similar conclusions about multiple agent interaction.

A final unique element is the notion that a reduction in the operator-vehicle ratio is likely to lead to an increase in situation uncertainty as stated by MPR. This seems like a logical statement, but one that designers have a tendency to forget. Control theory has the notion of controllability and observability. That is, a stable system has both observable states (states that can be sensed directly) that are controllable (can be influenced directly). However, states that can neither be influenced nor sensed directly have a greater chance of being unstable (i.e., increased uncertainty). The same principle may happen with a human operator with limited capacity to sense and influence all of the UMVs simultaneously. There are just too many variables to track.

3.5 SUMMARY

The purpose of this chapter is to inform the reader for the need to consider a theoretical framework throughout the life cycle of UUVs. The theoretical framework helps bound the problem and provides guidance on how to operate the new system. A large number of theoretical frameworks were reviewed for their relevance to UUVs and augmenting the Force by reducing the operator-vehicle ratio and/or optimising interoperability. Six frameworks were examined more closely, and it was shown that they do address the two objectives. Furthermore, the discussion led to the discovery of common and unique elements of the frameworks. The common elements were:

- Control Theory;
- Hierarchy;
- Sensing the world, own state, other actors, and understanding the mission objectives;
- Descriptive analyses; and
- Design philosophy and guidelines.

The unique elements were:

- Playbook;
- Mathematical analyses; and
- Reduced ratio means increased uncertainty.

3.5.1 Recommendations

The recommendations focus on the common elements while the unique elements act as a reminder to the designer as they consider their UUV systems.

The recommendation is that a UUV system designer should consider having a framework guide the design process. The framework should have elements of control theory and hierarchy. The framework should address sensing and understanding as much about the world, the actors in that environment, and the mission objectives. The framework should lead to descriptive analyses, although mathematical analyses would be helpful as well. The framework should yield design philosophies and design guidelines such as the situation uncertainty principle.

3.6 CHAPTER 3 REFERENCES

- [1] Forbes, K., Baker, K. and Youngson, G. (2005). Human-computer interaction between the operator and the semi-autonomous UAV team. Contract Report, DRDC Ottawa, Ottawa, Canada.
- [2] Kobierski, B. and Yves-Lamarre, J. (2004). Hierarchical Goal Analysis and Performance Modelling for the Control of Multiple UAVs/UCAVs from an Airborne Platform, Contract Report, DRDC Toronto, Toronto, Canada.
- [3] Kobierski, B., Coates, C. and Torenvliet, G. (2005). PCT-Based Analysis of ALIX Scenario for Crew Selection Research. Contract Report, DRDC Ottawa, Ottawa, Canada.

THEORETICAL FRAMEWORKS

- [4] Zhang, R. (2005). Prototype IAI for UAV Operators. Contract Report, DRDC Toronto, Ottawa, Canada.
- [5] Miller, G.A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81-97.
- [6] Boff, K.R., Kaufman, L. and Thomas, J.P. (Eds.) (1988). *Handbook of Perception and Human Performance*, John Wiley & Sons, NY, 1988.
- [7] Pigeau, R. and McCann, C. (2000). The Human in Command: Exploring the Modern Military Experience, edited by McCann and Pigeau, Kluwer Academic/Plenum Publishers, New York, 2000. Chapter 12: Redefining Command and Control, pp. 165-184.
- [8] Digney, B.L., Hubbard, P., Gagnon, E., Lauzon, M., Rabbath, C., Beckman, B., Collier, J.A., Penzes, S.G., Broten, G.S., Monckton, S.P., Trentini, M., Kim, B., Farrell, P. and Hopkin, D. (2004). Defence R&D Canada's autonomous intelligent systems program. In: *Proceedings of SPIE International Society of Optical Engineering Volume 5422 – Unmanned Ground Vehicle Technology VI*, G.R. Gerhart, C.M. Shoemaker, D.W. Gage, Editors, September 2004, Orlando, Florida, USA, April 2004, p. 13.
- [9] Department of Defense (2004). MIL-HDBK-46855A, Department of Defense Handbook: Human Engineering Program Process and Procedures. Record No. DDSM0123, August 2004.
- [10] Onken, R. (2002). Cognitive Cooperation for the Sake of the Human-Machine Team Effectiveness. In: *RTO-HFM Symposium on The Role of Humans in Intelligent and Automated Systems*. Warsaw, Poland. 7-9 October 2002.
- [11] Hollnagel, E., Nåbo, A. and Lau, I. (2003). A systemic model for Driver-in-Control. 2nd International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, July 21-24, Park City, Utah.
- [12] Hollnagel, E. and Woods, D.D. (2005). *Joint cognitive systems: Foundations of cognitive systems engineering*. Boca Raton, FL: CRC Press.
- [13] Hollnagel, E. (1993a). Models of cognition: Procedural prototypes and contextual control. *Le Travail humain*, 56(1), 27-51.
- [14] Hollnagel, E. (1993b). *Human reliability analysis: Context and control*. London: Academic Press.
- [15] Hollnagel, E. (2002). Time and time again. *Theoretical issues in Ergonomics Science*, 3(2), 143-158.
- [16] Powers, W.T. (1973). *Behavior: the control of perception*. Chicago: Aldine.
- [17] Farrell, P.S.E. (2003). Feedback in Error-correcting and Error-limiting Systems. In: *Proceedings of the 50th AGM & Conference of Canadian Aeronautics and Space Institute*, Montreal, Quebec, April 2003.
- [18] Craik, K.J.W. (1947). Theory of the Human Operator in Control Systems: The Operator as an Engineering System. *British Journal of Psychology* (38), 1947, pp. 56-61.

- [19] Miller, C. (2003). Delegation Architectures: Playbooks and Policy for keeping the operator in charge. A paper given at the Leiden Workshop for TG-078 Workshop. Smart Information Flow Technologies, 1272, Raymond Ave, St. Paul, MN 55108, U.S.A.

- [20] Macleod, I.S. (2003). System Processing and Task Organizational Model for Human Factors Verification and Validation. A paper given at the Leiden Workshop for TG-078 Workshop. Atkins Aviation and Defence Systems, 650 Aztec West, Almondsbury Bristol, BS32 4SD, UK.

Appendix 3-1: PHASE I – LITERATURE REVIEW

A3-1.1 LITERATURE SEARCH AND PRELIMINARY REVIEW

The project Statement of Work called for a Phase I survey to assess the scope (breath and depth) of the immediately available literature related to operator-agent interaction for intelligent adaptive interface design. The actual searching fields were beyond suggested areas such as tele-robotics and human computer interaction, they included supervisory control, information management and decision support, automatic manufacturing, medical diagnosis and consultation, and other social behaviour areas, etc.

The keywords were used in searching are: adaptive automation, adaptive interface, intelligent interface, and intelligent user interface. A number of databases were searched and included in Table A3-1.1.

Table A3-1.1: List of Databases Searched

Databases	Starting Year	Number of Hit
NTIS	1964	12
INSPECT	1969	4
Ei Compendex	1970	16
Biosis Previews	1969	5
EMBASE	1974	73
Pascal	1973	144
Transport Research	1970	63
Inside Conferences	1993	65
Mathscience	1940	239
SciSearch	1974	434
MEDLINE	1966	155
Information Science Abs.	1966	202
PsycINFO	1887	11

More than 500 abstracts were retrieved from all databases above, and there are 127 papers and reports were found likely relevant to the research domain and were requested. Totally, 82 papers and reports were reviewed as they have different focuses related to the topic of this research, as included in Table A3-1.2.

Table A3-1.2: Numbers of Papers in Different Research Domain

Domain	Number
Generic Review and Discussions	25
Architecture/Modelling, Technologies, and Implementations	30
Theoretical Models and Empirical Evaluations	27
Total	82

A3-1.2 PAPERS REVIEWED IN DETAIL

Of the literature identified in the search, and summarized in above section, a number of papers were selected for more detailed review. This list was developed based on a review of the abstracts of the literature list in Appendix 3-1, which are directly relevant to the topic of the project. While writing this report, there are two theses and three important report coming in as ordered. However, due to the time constraints, 10 most relevant papers (as list in Table A3-1.3) were reviewed in detail and summarized as below. The new literature will be reviewed against the current analysis in this report in the next phase that is to revise the draft framework of operator-agent interaction. The next section gives a short summary of the paper and brief comment on its applicability to our themes.

Table A3-1.3: Categorization of Literature Reviewed in Detail

Domain Relevance		Paper Number
	<i>Intelligent Interface Introduction and Principles</i>	1, 2
	<i>Theoretical Framework an/or Empirical Evaluation</i>	3, 4, 5, 6, 8, 9, 10
	<i>Operator-Interface Interaction Technology and Tools</i>	4, 5, 6, 7, 8, 9, 10
	<i>Agent Theory and Technology</i>	1, 7, 8
	<i>Adaptation, Automation Philosophy</i>	5, 6, 7, 8, 9, 10

A3-1.2.1 Special Issue on Intelligent Interface Technology: Editor's Introduction (Interacting with Computers, 12, pp. 315-322)

by Benyon, D.R. and Murry, D.M. (2000)

This paper discussed the reality of intelligent interface technology (IIT): “indirect management” of information against “direct manipulation”. Through explaining the purpose of the reference model as a useful way of thinking about IIT, the paper addressed the reasons why it is so difficult to represent fundamental psychological data about users. One of the reasons for focusing on psychological models is that these are characteristics which are most resistant to change in people and which can vary considerable between

THEORETICAL FRAMEWORKS

individuals (as high as 20:1 – i.e., one person may take twenty times as long as another to complete the same task). People can learn domain knowledge, but are less likely to be able to change fundamental psychological characteristics such as spatial ability. However, one of the difficulties with capturing psychological data is that the only signals that a computer can get are the sequences of tokens passed across the interface and attributes of that sequence such as timing information. Although this bandwidth will increase, it still remains very narrow compared to the wealth of information that we as human can perceive.

The definitions of the models used widely in IIT community were also given in the paper. It is a good introduction paper although there are more models in describing human-machine interaction.

- Domain models are abstract representations of the domain, so will not include the details.
- User models describe what the system “knows” about the user. Some systems concentrate on developing models of user habits, inferred by monitoring user-task interactions over time (i.e., by keeping a dialogue record). Other user profile data can often be most easily obtained by asking the user. Other systems try to infer user goals, although it is very difficult to infer what a user is trying to do from the data typically available to a computer system (mouse clicks and a sequence of commands). The user’s knowledge of the domain is represented in the student model.
- Interaction model: An abstract of the interaction (the dialogue record) along with mechanisms (such as a rule-based, a statistical model, a genetic algorithm, etc.) for making inferences from the other models, for specifying adaptations and, possibly, evaluating the effectiveness of the system’s performance.

A3-1.2.2 Steps to Take before Intelligent User Interfaces Become Real **(Journal of Interacting with Computers, Vol. 12, No. 4, pp. 409-426, February 2000)** by Hook, K. (2000)

This paper focused on four challenges for the intelligent user interface (IUI): usability demands, creating development methods, finding useful adaptations, and ensuring maintainability. The concept of an IUI as a means is to overcome problems that direct manipulation interface cannot handle: information overflow, cognitive overload. It demands better usability principles, better ways to improve the interaction, and better tools to survive the full life cycle of a system. The paper indicated that very few IUIs that have succeeded commercially have done their very simple adaptations based on simple knowledge of the user, or created their adaptations based on what other users do rather than some kind any complex inferred model of the user’s characteristics. That’s why there is a fear that IUI will violate usability principle and obscure the issue of responsibility. The main problem is not whether or not intelligence at the interface is possible or desirable – this depends on a lot on the task to be solved and the design of the total solution (with both adaptive and non-adaptive parts). Instead, we can see a number of problems not yet solved that prevent us from creating good applications. Therefore, there is a need to develop:

- Usability principles for intelligent interfaces (rather than direct-manipulation systems) that do not lead users’ expectations astray: control, transparency, and predictability; privacy and trust.
- Reliable and cost-efficient IUI development methods including functional, data, task knowledge, user, and environment analysis first.
- A better understanding of how and when intelligent can substantially improve the interaction (i.e., design practice). Proper evaluations of whether the system supports users’ real tasks must include an analysis of the organizational setting, users’ activities and cooperation with each other, usage of other tools, etc.

- Authoring tools that enable easy development and maintenance of the intelligent parts of the system (Scalability).

A3-1.2.3 Models for the Design of Human Interaction with Complex Dynamic Systems
(Systems Engineering & Management Handbook, 1999)
by Mitchell, C.M. (1996)

This paper overviewed the evolution of models of human-machine systems over the past forty years. From perspectives of cognitive engineering, ecological psychology, and naturalistic decision-making, the similarities between human-machine systems models and a variety of other recent approaches to understanding and aiding human interaction in real-world systems were described. The paper also proposed a set of tenets that characterizes models and human interfaces whose design is based upon them.

The paper described the trend of developing robust models with the same levels of fidelity as system models. The vision was to predict system and human behaviour and provide quantitative assessments of proposed system design. In 60' and 70', the crossover control model and the optimal control model (Wickens, 1984) focused on continuously tracking behaviour for fully manual tasks. However, with Digital Computer introduced, tasks are supervisory controlling of multiple subsystems. Since then, modeling goal changed from pursuing the development of a global and analytic/computational operator simulation (i.e., a quantitative, predictive model) to more focused: the development of system and task representations that could be used for the design of operator interfaces to complex dynamic systems, including displays, aids, and training systems. Therefore, the goal is no longer to produce a black-box human operator simulator that functions as robustly as traditional engineering models of system hardware and software, but rather the development of a useful description/prescription of the system-task-operator interactions. Understanding and modeling human cognition, problem solving, and decision-making became more and more popular and practical for the system design.

The essence of this paper is the emphasis of the importance of context as the central tenet of Human-Machine Systems Engineering. As Baron (1984) summarized this requirement succinctly: (A human-machine systems model) ... embodies the idea that to model human performance, one must model the system in which that performance is embedded. Human behaviour, either cognitive or psychomotor, is too diverse to model unless it is sufficiently constrained by the situation or environment; however, when these environmental constraints exist, to model behaviour adequately, one must include a model for that environment (the perspective of ecological interface design). Therefore, the system design should be context-oriented, descriptive, and prescriptive.

A3-1.2.4 A Theoretical Analysis and Preliminary Investigation of Dynamically Adaptive Interfaces
(International Journal of Aviation Psychology, 2001, Vol. 11, No. 2, pp. 169-195)
by Kevin B. Bennett, et al. (2001)

This paper described a dynamically adaptive interface (DAI), which changes display or control characteristics of a system (or both) in real time. The goal of this DAI is to anticipate informational needs for desires of the users and provide that information without the requirement of an explicit control input by the user. This research found that DAIs have the potential to improve overall human-machine system performance if they are properly designed. However, DAIs also have a very real potential to degrade performance if they not properly designed. This study explores both theoretical and practical issues in the design of DAIs. The relation of the DAI concept to decision aiding and automation was discussed, and a theoretical framework for design was also outlined.

In this paper, a preliminary investigation of the DAI design concept was conducted in the domain of aviation (precision, low-level navigation). Three interfaces were evaluated including: non-traditional controls (a force reflecting stick) and displays (a configurable flight director) were developed to support performance at the task; a standard interfaces (conventional controls and displays), a candidate interface (alternative controls and displays); and an adaptive interface (dynamically between the standard and candidate displays). The results indicated that significant performance advantages in the quality of route navigation were obtained with the candidate and adaptive interfaces relative to the standard interface; no significant differences between the candidate and adaptive interfaces were obtained; no significant differences between the candidate and adaptive interfaces were obtained. The implication of these results were discussed, with special emphasis on their relation to fundamental challenges that must be met for the DAI concept to be a viable design alternative.

This paper is a good example for human-machine interaction from theoretical development to empirical investigation to maximize overall performance. The design and comparison of three interfaces is a typical method for such kind of research. The results are also very interesting as they raised the issue of the dilemma for automation and adaptation. When, where, what, why, how to adapt is really a question theoretically and practically for better operator-machine, operator-agent interaction. The theoretical framework and research methodology are very useful for other similar research.

A3-1.2.5 Integrating Perceptual and Cognitive Modeling for Adaptive and Intelligent Human-Computer Interaction

(Proceedings of the IEEE Volume 90, Issue 7, July 2002, pp. 1272-1289)

by Duric Z., et al. (2002)

Through both theoretical analysis and empirical investigations, this paper is trying to advocates the technology and tools into interface design for intelligent human-computer interaction where human cognitive, perceptual, motor, and affective factors are modeled and used to adapt the human computer interface. The essence of the paper is to monitor affective behaviour or emotional behaviour or non-verbal information to answer W5 (i.e., what why, where, when, and how) and adapt the display according to this behaviour. The method for interface design is more human-like in which the interface/machine or the agent/automation embedded is regarded as another human assistant who can monitor perceptual and cognitive levels and understand the “partner” or “teammate”, thus react for better collaboration with better overall results. The idea is to emphasis the team collaboration, which is true and good in human-human interaction.

“It is not only computer technology that needs to change to make such novel interfaces a reality. People have to change as well and adapt to the interface that the computer presents them with. In the end, both people and the computer have to understand each other’s intentions and/or motivations, provide feedback to each other as necessary, and eventually adapt to each other.”

A3-1.2.6 Adaptive Interfaces for Human-Computer Interaction: A Colourful Spectrum of Present and Future Options

(IEEE International Conference on Systems, Man and Cybernetics, 1995, Volume 1, 292-297)

by Balint, L. (1995)

This paper discussed what kind of adaptations could be built into the interfaces allowing human-computer interaction from different aspects of human behaviour: by its nature, physiological attributes (eye, ears, fingers, etc.), intellectual characteristics (capacity, recognition, learning, decision, etc.), knowledge basis (knowing the environment, the system, him/herself, etc.) and psychological states (concentration, vigilance, fatigue, patience, etc.). As pointed out in the paper, that adaptive interfaces should be capable of:

- Adjusting the forms of information transfer;
- Transforming the information contents;
- Altering/merging modes of information flow; and
- Exchanging/combining communication media.

The paper also discussed the future of adaptive interfaces, the role of formal interaction modeling, the importance of abstract/structural interface hierarchy, the integration of interaction modes and media, the sophistication of interface modularity and the exploitation of the advantages in combining/integrating conceptual-functional-physical design aspects. It is a good reference of Taxonomy of Adaptive Interfaces.

A3-1.2.7 Intelligent User Interfaces: An Introduction
(International Conference on Intelligent User Interfaces 1999 ACM Press)
by Maybury, M. (1999)

This paper introduced the concept of intelligent user interfaces (IUI) which aims to improve the efficiency, effectiveness, and naturalness of human-machine interaction by representing, reasoning, and acting on models of the user, domain, task, discourse, and media (e.g., graphic, natural language, gesture). As indicated in the paper, IUIs are multi-faceted, in purpose and nature, and include capabilities for multi-media input analysis, multi-media presentation generation, and the use of user, discourse and task models to personalize and enhance interaction.

Two important areas addressed in the paper are agent based interaction and evaluation. Research on agent technology has increased in prominence in applications, which includes the use of agents to express system and discourse status via facial displays, multi-modal communication between animated computer agents, and standards and open architectures for building agent based multi-modal interfaces – but the key questions are: what can and should an agent do? How they should do it? How, when and why should they interact with the user when doing it? In terms of evaluation, it can be glass-box (internal) and black-box evaluation (end-to-end). Criteria for evaluation might include quantitative ones (e.g., time to perform tasks, accuracy of tasks, percent of inter-assessor agreement) as well as qualitative ones (e.g., user indication of utility, ease of use, naturalness). This is a good reference for the process of developing and testing agent technology based interfaces.

A3-1.2.8 The Future of Watchstation Design: Evolution from Single Purpose to Intelligent Watchstations
(2002 Command and Control Research and Technology Symposium, Naval Postgraduate School, Monterey, California, 11-13 June 2002)
by O'Donnell, L. (2002)

The focus of this paper is to address the issues in interface design and the changes in the console design to support distributed mission task activities for joint operations of global command and control systems. Increased mission demands combined with smart weapons, automated functions and increased collaborative warfighter functions have increased the multi-tasking requirements to be accomplished. Humans in a warfighter role have shifted from a narrow task focus within a narrow job focus of a single purpose watchstation and a high human-in-the loop interface workload, to becoming controllers of these distributed systems and collaborative activities. In the paper, current watchstation design was described that requires the human to perform manual system operations in combination with numerous independent synchronous activities such as communications and adjacent equipment operations. Future watchstation will need to be

designed to support the work environment with: increased multi-tasking capabilities, dynamic monitoring of task process, integrated system designs, and improved distributed team collaboration task capabilities. Advances in technology have enabled the design of an effective watchstation design that will allow for multi-modal user interfaces best suited to the task. Future watchstation designs should also utilize self-adaptive interfaces, increased visual workspaces, agent technologies, integrated speech, and visual and direct touch methods to reduce the human-interface workload and streamline the tasks. All these features are required for future UAV/UCAV control interfaces.

The paper not only analyzed the current trends and advantages of intelligent interfaces (watchstations), but also brought up a smart agent taxonomy to construct the flexible, dynamic, scalable, and robust distributed system capabilities over system networks as multiple agent systems. Although the context discussed in the paper was not focused on airborne multiple UAV control, but the discussions of several key technologies to enabling an intelligent system and future research recommendations on intelligent user interface design can be generally applied to any design of the framework for optimal operator – agent interaction.

A3-1.2.9 An Architecture for Intelligent Interfaces: Outline of an Approach to Supporting Operators of Complex Systems
(Human Computer Interactions, 3(2), pp. 87-122)
by Rouse, W.B., Geddes, N.D. and Curry, R.E. (1997-1998)

This paper described a concept of a comprehensive support system design for operators of complex systems. A variety of difficult design issues as well as ongoing efforts aimed at resolving these issues were also addressed.

The main focus of the paper is addressing two methodology issues to the design: design methodology and automation philosophy. Although the suggested design methodology follows the traditional human factors engineering principles, automation philosophy emphasises on maximizing overall performance by overcoming human limitations and enhancing human abilities. The focus of the paper (which is different from many other literatures) is the emphasis of automation as a backup – the default modes are usually manual with automation invoked only when either anticipated operator performance is unacceptable or the operator chooses to relinquish control. With the adoption of this operator-centred automation philosophy, an architecture including intelligent management of information and tasks was proposed. Within it, the concept of operator state is central to the functioning of the components of the intelligent interface. The relevant elements include: activities, awareness, intentions, resources, performance. Another component is the interface manager which is similar to an executive's assistant who zealously guards the superiors' time and resources. Although two important questions were raised: when and how to automate, there was still no answers in the paper. Another important question of what to automate was not addressed in the paper either. The paper discussed a nice layout of the architecture for complex system design, but it did not cover enough cognitive and perceptual aspects of a dynamic, complex, and interactive system, especially for multiple UAV/UCAV control. The concept of automation control in the paper may not apply to the supervisory control mode in the UAV case, where, it is still operator centred design, but automatic agents/ assistants will play significant roles.

A3-1.2.10 A Model for Types and Levels of Human Interaction with Automation
(IEEE Transactions on Systems, Man and Cybernetics, 30 (3), pp. 286-297)
by Parasuraman, R., Sheridan, T.B. and Wickens, C.D. (2000)

A framework/model was proposed for types and levels of human interaction with automation (Sheridan's 10 points scale). They also proposed four broad classes of functions which automation could be applied from information processing point of view:

- a) Information acquisition;
- b) Information analysis;
- c) Decision and action selection; and
- d) Action implementation.

Within each of these types, automation can be applied across a continuum of levels from low to high, from fully manual to fully automatic. A particular system can involve automation of all four types at different levels. Since automation does not merely supplant but changes human activity and can impose new coordination demands on the operator, appropriate selection is important based on the primary and secondary evaluative criteria. The primary criteria look at human performance consequences: mental workload, situation awareness, complacency, and skill degradation. The second criteria include the automation reliability and the costs of consequences.

Although the paper considered human machine interaction mainly from information process point of view, the proposed model can be taken as a good starting point for considering what types and levels of automation should be implemented in a particular system. The paper is concerned with human performance in automated systems and emphasizes human-machine comparison. Automation is defined as a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator. The paper also touched a little bit on action automation – agents which track user interaction with a computer and execute certain sub-tasks automatically in a contextually-appropriate manner. However, this area should be elaborated more associated the theory developments and empirical investigations (which is the future work as mentioned in the paper). Even in the proposed model, the issue in whether automation unreliability has similar negative effects for all four stages of automation needs further examination. Regarding costs of decision/action outcomes, individual differences between users in the same interface should be addressed more, especially on user profile building on the interface (user modelling embedded in interface). It is good to point out that empirical work needs to be done to explicitly compare the effects on human performance of different levels of automation for information acquisition and analysis, in other words, the levels of interface intelligence. Overall, this paper emphasised more function allocation between user and machine regarding automation, but less was discussed on operator interface interaction. How the automation should perceive, analyze, understand, react, and collaborate with user as an agent or assistant still remains untouched.

A3-1.3 COMMENTS ON THE LITERATURE REVIEWED IN DETAIL

Despite a fairly significant investment in research over the past decade, there is still no generic framework or architecture covering all aspects of human-machine interaction and the relevant technologies. In particular from a Human Factors Engineering perspective, the lack of empirical investigations on validating proposed frameworks makes many designs costly and ineffective. Many existing models either focus on user's models or task/domain models, rather than interaction models.

A3-1.3.1 What Does Interaction Model Do?

The supervisory control often only implicitly implies models of representing monitoring/situation assessment system variables, states, or aggregate measures, especially when supervisory control systems become more sophisticated. However, the human operator models explicitly represent the domain of application, task constraints, and the flexibility inherent in human interaction with a complex system. Thus, the interaction models need to reflect the work environment and its dynamic nature, as perceived by the operator given the

THEORETICAL FRAMEWORKS

current system state and current system goals. The model of control activities must represent at least three properties of both the control and controlled systems and the operator supervising them:

- 1) What changes to the system the operator wants to make;
- 2) Why the changes should be made, with respect to system goals and current state; and finally
- 3) How the needed changes to the system can be made, i.e., the operator activities undertaken to bring about the desired state.

These models should represent the concurrent nature of the control activity and the choices available to the operator given current system state. To be useful to the design, an effective model must be both descriptive and prescriptive to describe what operator actually do and specifies what an operator should do.

Figure A3-1.1 illustrates the relations of user, system, and the interaction between them. In which, user can act as a board of directors of a corporation, and the system can be regarded as many agents assisting the CEO who is the intelligent interface. In order to help the board members to make decision, through CEO, agents will provide necessary information to keep the board members informed what is currently being done and what is going to happen at the next stage (descriptive and prescriptive). At the same time, agents will monitor the board members' cognitive workload and performance, and guard the resources and time. Agents can also learn from past experience and change how they behave in given situations (adaptive). Agents will communicate and cooperate with other agents and act according to the results of that communication (cooperative). Therefore, user-system interaction basically is user-agent interaction for general cases. Here, agent technology is taken as a means to facilitate the interaction between user and agents, which is the topic in next section.

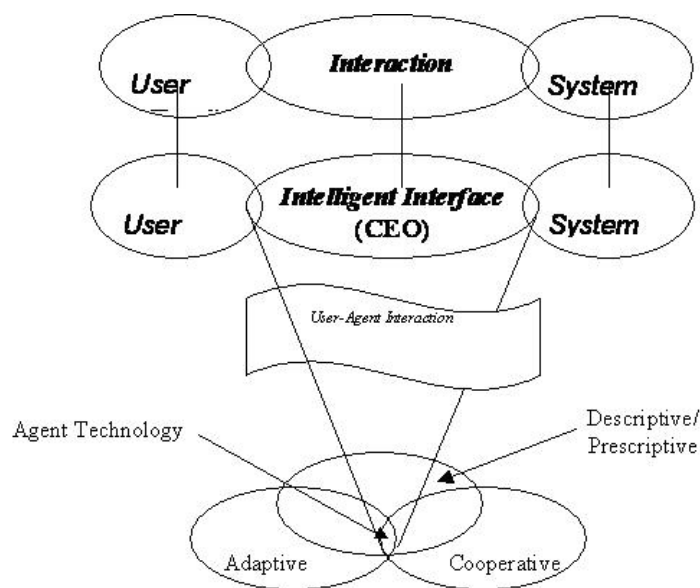


Figure A3-1.1: Relation of User System Interaction.

A3-1.3.2 What Key Functions should an Interface Have?

Key functions within the user-system architecture include information management, error monitoring, and adaptive aiding. One of the central knowledge sources underlying this functionality is an operator model that

involves a combination of algorithmic and symbolic models for assessing and predicting an operator's activities, awareness, intention, resources, and performance.

The intelligent interface should also have many features to support:

- More efficient interaction – enable more rapid task completion with less work.
- More effective interaction – doing the right thing at the right time, tailoring the content and form of the interaction to the context of the user, task, dialogue.
- More natural interaction – supporting spoken, written, and gestural interaction, ideally as if interacting with a human interlocutor.

A3-1.3.3 What Interaction Level should an Interface Have?

As pointed out by Lajos (1995), more complex adaptivity schemes should require and/or allow:

- More levels of interaction;
- More media and modes (content and form) of interaction;
- Involvement of more personal shaping factors into adaptation;
- Wide choice of skill-based, rule-based and knowledge-based interaction elements; and
- More modularity/hierarchical levels in the interface structure and functions.

The moral behind this is that people see not only with the eyes, but with the brain as well. In other words, perception involves a whole and purposive cognitive process. From another perspective, people are selective on their attention [8]. In other words, attention is not decided by what being presented (perception process), but what being decided by the brain (cognitive process). People tend to forget what has been seen and what has been heard, especially in a complex, dynamic, and challenging environment. The proactive feedback system can better serve the purpose of communicate between user and interface for adaptation. There are certain technologies and models can be used for such kind of intelligent system.

Other communication channels between user and interface should be considered as well such as verbal and aural inputs. Multi-modal inputs are good for monitoring and communicating between user and interface, but the more information being provided and processed, the more stress and workload for the interaction. The appropriate level and channel of input and interaction should depend on the task itself. The reliability and accuracy for those user models and algorithms are also critical for the whole system. It should also involve trust and transparency issues: Trust, when the agent does things automatically; Transparency, when the interface/agent effectively disappears, thus, enabling the user to interact directly with the objects of interest in the domain and to achieve effective interaction with a minimum of cognitive effort. A dynamic adaptive interface/agent should automatically provide information without the requirement for control input by the user with the help of cognitive inference aid.

Figure A3-1.2 illustrates the three variables of human-machine interfaces: level of (task) complexity, level of (interface) intelligence, and level of (user-interface) interaction. Task complexity is decided by the nature of task (e.g., the number of vehicles to control, the level of stress, etc.). Interface intelligence is decided by agent technology, and it should cover all aspect of human perception, behaviour, and cognition. It is also related directly to automation level – how much work being done by the agents automatically. User's interaction depends on both the levels of task complex and interface intelligence. Obviously, if the level of task

THEORETICAL FRAMEWORKS

complexity is high and automation level is low, then the user would probably interact more – but how much user interaction really depends on the nature of the task and the interface.

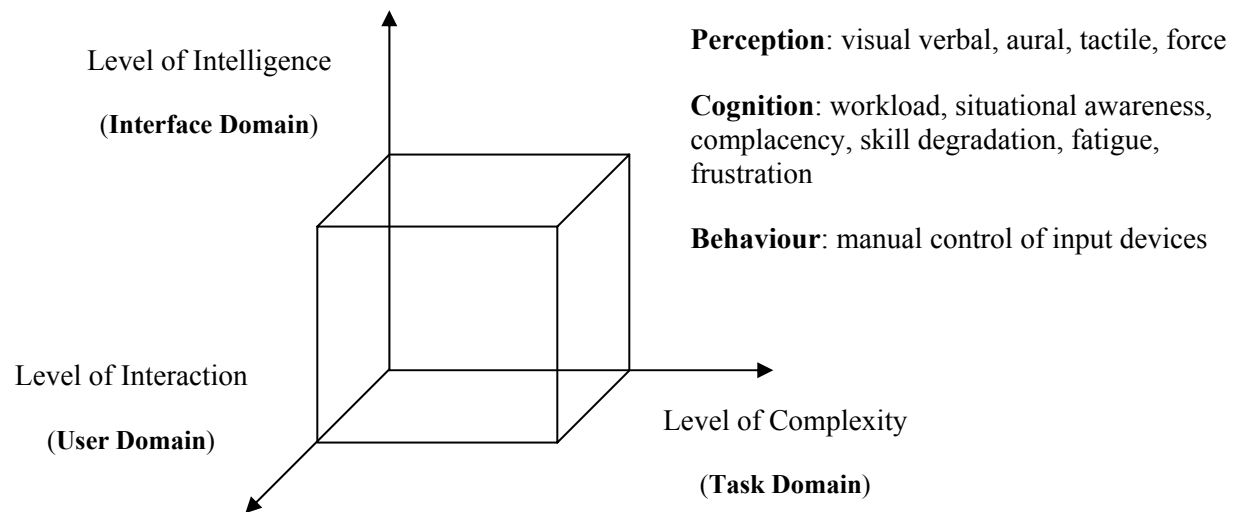


Figure A3-1.2: Taxonomy of Human-Machine Interaction.

Appendix 3-2: COMMENTS ON THEORETICAL FRAMEWORK FOR UNINHABITED MILITARY VEHICLES

Erik Hollnagel

In the following I shall attempt to comment on the points raised in the letter from Phil Farrell, in the ongoing work on NATO RTO HFM TG-017. The comments refer to the theoretical framework that I presented at the meeting in Leiden, 2003. This framework is referred to as the Extended Control Model (ECOM). The model was outlined in the presentation given at the meeting in Leiden, and has also been described in a conference paper [1] and a book chapter in [2]. The pedigree of the model includes the description of the principle of contextual control [3], the initial contextual control model [4], and the fully developed contextual control model [5].

These comments do not include a detailed description of the model. For details, see Chapter 7 (Section 7.7). Briefly explained, the model provides a framework for describing how a joint cognitive system can maintain control of a situation or a process. A cognitive system is defined as “a system that can modify its behaviour on the basis of past experience so as to achieve specific entropic ends.” A joint cognitive system can be any combination of humans and machines (technological artefacts) or humans and humans (social groups/organisations). The model invokes the principle of multiple, simultaneous layers of control. The layers are hierarchically organised with one or more instances at each layer. Control layers differ with respect to the time window or time horizon they cover, as well as in the balance between feedback and feedforward control. The model currently describes four layers of control called (from the top down) targeting, monitoring, regulating, and tracking. It is applicable both to single systems (e.g., a driver and a vehicle) and to larger entities and organisations.

I should make clear that my experience is primarily from applications outside the military, typically process industries and transportation (surface, air, space), where I have been working with issues of automation, human-machine interaction, and risk and reliability.

A3-2.1 FORCE MULTIPLICATION

- Does the framework/model address operator to UMV ratio issues?
- Does the framework/model address interoperability issues?

ECOM will enable a modelling of the joint system (i.e., multiple operators and multiple UMVs), thereby making possible an evaluation of specific allocations. The question of a ratio as such cannot be answered, since it will depend on the type of scenario, on situational demands (and resources), time constraints, urgency, etc. ECOM will enable a constructive discussion of allocations for different types of scenarios, but not provide any automatic answers – as there are none!

I am not certain what exactly is meant by interoperability issues. In computer science it refers to the ability to exchange and use information at different locations or points in a system, such as a network. ECOM will not address interoperability directly, but will give guidelines about which information is needed – at different points – to maintain control of the joint system. In that sense interoperability is indirectly addressed. In cases where maintaining control is critical, this may lead to considerations of redundancy (of control), hence to interoperability issues.

THEORETICAL FRAMEWORKS

A3-2.2 UMV SCENARIO / USE CASES

- Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?

ECOM is not domain specific, and can therefore be applied to different types of UMVs. As noted above, it can also be applied to different levels of system aggregation, since the unit of analysis is the joint system. To do so requires a clear definition of the system boundaries, since these are functional rather than structural (i.e., not necessarily defined in relation to physical entities.)

A3-2.3 THEORY EVALUATION

- Has the framework/model been evaluated, tested, and applied to commercial or military operations?
- Do you have an example, closely related to UMV situations, where the theory was implemented?

An early version of ECOM has been used in a military context [6] The model has also been used in research on joint driver-vehicle systems (automobiles) (Hollnagel, Nåbo & Lau (2003), and to model planning and maintenance at a nuclear power plant during a short outage [7] An example closely related to UMV will be developed during the fall, in collaboration with Robert Taylor and sponsored by FMV, Sweden.

A3-2.4 REFERENCES

- [1] Gauthereau, V. and Hollnagel, E. (2004). Stepping away from the centralization/decentralization struggle: planning, control, and adaptation at a Swedish nuclear power plant. *European Management Journal* (in print).
- [2] Hollnagel, E. (1993a). Models of cognition: Procedural prototypes and contextual control. *Le Travail humain*, 56(1), 27-51.
- [3] Hollnagel, E. (1993b). *Human reliability analysis: Context and control*. London: Academic Press.
- [4] Hollnagel, E. (2002). Time and time again. *Theoretical issues in Ergonomics Science*, 3(2), 143-158.
- [5] Hollnagel, E., Nåbo, A. and Lau, I. (2003). A systemic model for Driver-in-Control. 2nd International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, July 21-24, Park City, Utah.
- [6] Hollnagel, E. and Woods, D.D. (2005). *Joint cognitive systems: Foundations of cognitive systems engineering*. Boca Raton: CRC Press.
- [7] Worm, A. (2001). Breaking the barriers: Facilitating efficient command and control in multi-service emergency management. 8th World Conference on Emergency Management (TIEMS), June 19-22, Oslo, Norway.
- [8] Bonnef, Y.S., Cooperman, A. and Sagi, D. Motion-induced blindness in normal observers. *Nature* 411, 798-801 (2001).

Appendix 3-3: REQUEST FOR COMMENTS ON THEORETICAL FRAMEWORKS FOR UNINHABITED MILITARY VEHICLES

Chris Miller, Ph. D.

Smart Information Flow Technologies
2119 Oliver Avenue South
Minneapolis, MN 55405-2440
USA

(612) 578-SIFT (7438)
(612) 374-4668

Reference: Action Items from Sweden Meeting, March 2004

The NATO RTO Human Factors and Medicine Panel Task Group 017 entitled, “Uninhabited Military Vehicles (UMVs): The Human Factors of Augmenting the Force” is studying ways to augment military Forces by leveraging the potential advantages of UMVs to act as force multipliers. A specific goal of the Task Group is to produce a NATO report that would identify, prioritize, and address the Human Factors issues associated with integrating UMVs into the Force. The Task Group (TG) believes that “Augmenting the Force” will require research and development in the following areas:

Collaborative Work – Optimal Task Distribution

- Virtual team performance
- Manned/Unmanned collaboration
- Interoperability
- Flexible level of automation
- Optimization of operator/vehicle ratio

Control Stations – Intelligent Operator Support

- Operator functional state assessment
- Intelligent adaptive interfaces
- Cognitive cooperation
- Knowledge management systems

Simply put, the Force will be augmented by:

- a) Reducing the operator/vehicle ratio; and
- b) Improving interoperability, and both require Human Factors input.

The Task Group has organized the Human Factors of augmenting the Force into five primary theme areas (Enclosed is a short synopsis of each):

- Theoretical Frameworks
- System of Systems

THEORETICAL FRAMEWORKS

- Supervisory Control
- Levels of Automation
- Advanced Interfaces

Theoretical frameworks/models were identified from the literature as well as the Leiden Workshop held in June, 2003 that may help in the development of the four other themes. However, we would like to solicit comments directly from the authors on their framework's relevance with respect to reducing operator/vehicle ratio and improving interoperability.

Therefore, we invite you to comment on your theory with respect to the following:

A3-3.1 FORCE MULTIPLICATION

- Does the framework/model address operator to UMV ratio issues?
- If so, how could the framework/model help reduce the ratio?

PB allows flexible levels of control to be used by the operator depending on need, trust, workload, etc. As such, in principle, it permits a single operator to do everything from joystick control to swarm control of any number of UAVs. Of course, the level of aggregation of the behaviour defined by the “plays” which the operator can plausibly use to control must be more aggregated the more vehicles controlled – you can plausibly tell 300 UAVs to execute a “secure area” play, tell a team of 4 UAVs a specific flight route to fly to maintain surveillance of a city block, or provide dynamic joystick inputs (which could be thought of as micro-plays – e.g., “Actuate Flaps: 30 degrees”) for a single UAV, but not provide joystick inputs to 300 UAVs simultaneously.

- Does the framework/model address interoperability issues?
- If so, how could the framework/model help improve interoperability?

Plays, especially higher level plays, can be defined as abstract functions to be fulfilled in alternate ways by various combinations of variously capable UAVs – with the details associated with controlling the specific UAVs buried in finer-grained, lower level plays. SIFT has, in fact, recently demonstrated the ability for a user to command a comparatively high level play (“Overwatch” = sustained surveillance of an area) without reference to the specific vehicle(s) which will provide it. When operating at the higher levels of the play hierarchy, the user simply commands/requests a “service” and leaves it the PB to determine how to best provide that service given the available UAV resources – in our demonstration, potentially multiple instances of two types of heterogeneous UAVs (a rotary winged GT-Max and a fixed wing Dakota) which might have different current locations, fuel resources, onboard sensors, etc. The user can also provide constraints that limit the range of lower level plays that are acceptable – e.g., requiring that an infrared sensor be used for the Overwatch and, thereby, eliminating from consideration any plans that would involve a UAV that doesn't have that sensor type. Thus, PB achieves interoperability by building the knowledge about how to utilize different resources into PB's Planner and leaving the user free to simply define the kind of service s/he requires and leaving it to the PB to decide how best to provide it.

A3-3.2 UMV SCENARIOS / USE-CASES

- Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?

Anywhere we can define useful aggregations/patterns of repeatable behaviours (and codify the knowledge about how to achieve them) into a hierarchical play representation, PB is useful.

A3-3.3 THEORY EVALUATION

- Has the framework/model been evaluated, tested, and applied to commercial or military operations?

See Parasuraman, [1] for empirical evaluations of portions of delegation-style interactions. PB has been applied in simulation to multiple UAV tasking scenarios and platforms, a UGV application and we are currently working on developing an application using PB to allow a designer to “task” a human performance simulation with play-like mission scenarios in order to do, for example, workload analyses during platform design.

- Do you have an example, closely related to the UMV situations, where the theory was implemented?

Yes, several. Our current DARPA UAV project, PVACS is our richest implementation thus far.

In answering these questions, you may wish to compare and contrast your theory with traditional or other approaches. Also, please include references to the theory if available (electronic copies preferable). We anticipate that your response will be 1 to 3 pages, however there is no set limit.

A3-3.4 REFERENCES

- [1] Miller, C. and Parasuraman, R. (in revision). “Designing for Flexible Human-Automation Interaction: Playbooks for Supervisory Control.” Submitted to Human Factors.
- [2] Parasuraman, R., Galster, S., Squire, P., Furukawa, H. and Miller, C. (submitted). A Flexible Delegation-Type Interface Enhances System Performance in Human Supervision of Multiple Robots: Empirical Studies with RoboFlag. Submitted for inclusion in IEEE Systems, Man and Cybernetics – Part A, Special Issue on Human-Robot Interactions, Julie Adams (Guest Ed.).
- [3] Squire, P., Furukawa, H., Galster, S., Miller, C. and Parasuraman, R. (Accepted) Adaptability and flexibility are key! Benefits of the “Playbook” interface for human supervision of multiple unmanned vehicles. To be included in Proceedings of the 2004 Meeting of the Human Factors and Ergonomics Society, September 20-24, New Orleans, LA.
- [4] Miller, C., Goldman, R., Funk, H., Wu, P. and Pate, B. (2004). A Playbook Approach to Variable Autonomy Control: Application for Control of Multiple, Heterogeneous Unmanned Air Vehicles. In: Proceedings of FORUM 60, the Annual Meeting of the American Helicopter Society, Baltimore, MD, June 7-10.
- [5] Miller, C. and Parasuraman, R. (2003). Who’s in Charge?; Intermediate Levels of Control for Robots We Can Live With. In: Proceedings of the 2003 Meeting of the IEEE Systems, Man and Cybernetics society, October 5-8, Washington, DC.
- [6] Parasuraman, R., Galster, S. and Miller, C. (2003). Human Control of Multiple Robots in the RoboFlag Simulation Environment. In: Proceedings of the 2003 Meeting of the IEEE Systems, Man and Cybernetics Society, October 5-8, Washington, DC.

THEORETICAL FRAMEWORKS

- [7] Miller, C., Parasuraman, R., Lee, J., Corker, K., Johnson, L. and Schreckenghost, D. (2003). The Etiquette Perspective for Human-Automation Relationships: Applications, Models and Results. In: Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society, October 13-17, Denver, CO.
- [8] Lintern, G. and Miller, C. (2003). Identification of Cognitive Requirements for New Systems. In: Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society, October 13-17, Denver, CO.
- [9] Miller, C. and Parasuraman, R. (2003). Beyond Levels of Automation: An Architecture for More Flexible Human-Automation Collaboration. In: Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society, October 13-17, Denver, CO.
- [10] Miller, C., Goldman, R., Funk, H. and Parasuraman, R. (2003). Delegation Systems: Staying in Charge of Highly Flexible Automation. In: Proceedings of the 10th International Conference on Human-Computer Interaction, June 22-27, Crete, Greece.
- [11] Miller, C., Goldman, R., Funk, H. and Parasuraman, R. (2002). Delegation as a Model for Human-Automation Interaction. In: Proceedings of the 3rd International NASA Workshop on Planning and Scheduling for Space, October 27-29, 2002, Houston, Texas.
- [12] Miller, C., Pelican, M. and Goldman, R. (1999). High Level 'Tasking Interfaces' for Uninhabited Combat Air Vehicles. In: Proceedings of the International Conference on Intelligent User Interfaces, January 5-8, Redondo Beach, CA.
- [13] Miller, C. and Goldman, R. (1997). "Tasking Interfaces; Associates that know who's the boss." In: Proceedings of the 4th USAF/RAF/GAF Conference on Human/Electronic Crewmembers, September 22-26, Kreuth, Germany.

Appendix 3-4: REQUEST FOR COMMENTS ON THEORETICAL FRAMEWORKS FOR UNINHABITED MILITARY VEHICLES

Patrik Stensson
Swedish Air Force

The theory “The Human Axiom” or “The Philosophical Framework for Military Relevance”

A3-4.1 FORCE MULTIPLICATION

- Can the framework/model help in reducing the operator to UMV ratio?

Yes, but only indirectly through the ability of assessing the requirements for having appropriate human control, the requirements for making the human be appropriately in charge. Not unlikely, it will help in increasing the operator to UMV ratio instead of reducing it! And, the main issue is that the theory argues precisely that the most valuable military effect is related to appropriate human control, and on the contrary, inappropriate human control leads to a reduced military effect. That is, the theory states that gain of military effect, force multiplication, is achieved by having appropriate human control. This is the concept of designed and applied effect.

- How could the framework/model help reduce the operator to UMV ratio?

It may help in establishing the prerequisites for human control from an operational perspective, in order to make technological solutions military relevant.

- Can the framework/model help with interoperability issues?

Yes, since interoperability consists of a significant amount of human interoperability, appropriate human control is necessary to achieve interoperability.

- How could the framework/model help with interoperability issues?

See above...

A3-4.2 UMV SCENARIOS / USE-CASES

- Does the theory cut across UMV situations?

Yes, it's completely general.

A3-4.3 THEORY EVALUATION

- Is the framework/model implementable and testable?

I don't know

- Do you have an example, closely related to the UMV situations, where the theory was implemented?

No!!!!!!!!!!!!!!!!!!!!!!

Appendix 3-5: REQUEST FOR COMMENTS ON THEORETICAL FRAMEWORKS FOR UNINHABITED MILITARY VEHICLES

Phillip Farrell, Ph. D.

A3-5.1 DESIGN IMPLICATIONS FOR MULTIPLE AGENT SYSTEMS

As machines become more “intelligent”, humans will insist on interacting with them as they do with other humans, otherwise humans may reject the intelligent agent technology that is expected to be part of future UMV systems. In this context agents may be human as well as software.

A framework is proposed based on Perceptual Control Theory [1] to model multiple non-interacting and interacting agents in order to understand the system dynamics that would lead to design implications for user-intelligent agent interaction [2]. PCT describes human cognition as a means-end hierarchy of control units. Each control unit involves the control of a perception. At the lowest levels, control is subconscious and can might be described by classical linear control theory. At the highest levels, control is conscious, and deliberate requiring rule-based thinking, logic, and reasoning. Regardless of the hierarchical level, the control law remains the same – the output of each control loop attempts to drive the perception closer to its internal goal. The key advantage of modelling agents using PCT is that one can apply all the mathematical power of Control Theory, which includes stability and optimization analyses.

It is assumed that multiple agent interaction is more like human-human interaction than it is like human-machine interaction. Table A3-5.1 lists some key differences:

Table A3-5.1: Critical Differences between Human-Machine and Multiple Agent Interaction

Human – Machine Interaction (HMI)	Multiple Agent Interaction (MAI)
Plans, actions and system states are known or knowable within limits.	Plans and actions are not necessarily known a priori, and may produce unexpected system states.
HMI is specific, systematic, and often associated with Standard Operating Procedures.	MAI is fuzzy and there may be many means to achieve the same end.
Human has beliefs (assumptions) about the machine and the task. The machine design takes into consideration certain assumptions about the human and the task.	One agent has beliefs (assumptions) about other agents and the task, and those beliefs may be hierarchical and dynamic.
Typically trust is binary – the machine works or the machine does not work.	Trust must be built over time because it becomes more a function of mission completion and success rather than based on an individual agent’s work.
Typically there are two levels of automation – fully manual or fully automatic.	Potentially there could be a gradient of automation.

Human – Machine Interaction (HMI)	Multiple Agent Interaction (MAI)
It is possible to know how the system processes information (i.e., outputs can be reconstructed from the inputs).	It may be difficult, if not impossible to trace information flows in and amongst multiple agents.
The context is typically static or well-defined.	The context is dynamic and sometimes unknown a priori.
Only the human is truly autonomous.	Potentially there could be multiple truly autonomous agents.

From a control theory perspective, human-machine interaction may be analysed by treating the machine as a simple input-output transfer function with some known disturbances – this problem is relatively easy to solve. On the other hand, multiple agent interaction must be treated as independent (truly autonomous) control loops that interact through a common portion of the world (often called the interface). Conceptually, this model would produce a different set of dynamics that are unstable and not easily predictable. The clear advantage is that multiple agents have the potential to multiply the force.

Two interacting agents as well as a generic multiple agent model was analysed using mathematical control theory techniques and the following are a list of design recommendations that come from this modelling exercise:

- Closed-loop feedback modelling techniques can be used in the design of multiple agent systems.
- Designers should consider goals, sensing and decision-making strategies, and world states as part of their system design.
- Agents should act on separate states, while gathering data from all sources.

These design principles have been applied to UMV research studies on the design of intelligent adaptive interfaces, and selecting crews for UAV operations. The third design philosophy was applied to information management business rules for the Multi-National Experiment 4 on Effects Based Operations with US Joint Forces Command as the experiment lead. This experiment involved over one hundred players over a distributed network from countries around the world. The interface design and business rules were critical in order to successfully collaborate and conduct the experimental operation.

This paper models intelligent agents using Perceptual Control Theory. Using standard mathematical control theory techniques, conditions for stability are derived for two-agent and multiple agent interactions.

A3-5.2 FORCE MULTIPLICATION

- Does the framework/model address operator to UMV ratio issues?

Yes. The theory has the potential to determine, a priori, conditions for stability for any operator/vehicle configuration.

THEORETICAL FRAMEWORKS

- If so, how could the framework/model help reduce the ratio?

The theory can show that as one increases the number of intelligent agents, there will be as many regions of local instability as there is stability. Thus, the design would need to be constrained more and more in order to maintain a stable trajectory through the state space. The theory has the potential to show optimal trajectories through the state space as the ratio is reduced.

- Does the framework/model address interoperability issues?

Yes.

- If so, how could the framework/model help improve interoperability?

One of the design implications of this stability analysis is that multiple agents can gather information from each other and the world, but must act on separate parts of the world. This principle is best illustrated with a wheel barrel example. Two people pushing one wheel barrel may have similar goals and perceptions, but if their actions are not precisely coordinated then the system will quickly become unstable. Similarly, two forces may want the information from sensors onboard a UMV, but if they attempt to control the vehicle and/or sensors simultaneously (or even time divplexed) there is great potential for conflicts. What this means for interoperability is that standards might be required to ensure proper sensing of information, and action must be coordinated (perhaps proceduralized) to ensure de-confliction.

A3-5.3 UMV SCENARIOS / USE-CASES

- Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?

Yes. The paper describes generic multiple agent interactions. It does not distinguish between animate and inanimate, human or machine. In order to do the mathematics, however, it does make a fundamental assumption of linearity – and we know that these UMV situations are not linear. Control theorists have methods to deal with non-linear systems including piece-wise linearization. Thus the linear stability conditions only approach the real stability conditions as the linear pieces reduce in size. Lyapunov approaches to deriving stability conditions provide a global solution to nonlinear dynamical systems, however, the challenge is to derive (often stumble onto) a Lyapunov function that satisfy certain energy criteria. I think the best the Theory can do is provide heuristics, but it can provide it to any UMV situation.

A3-5.4 THEORY EVALUATION

- Has the framework/model been evaluated, tested, and applied to commercial or military operations?

Yes. This first application of these design considerations hope to be in the Adaptive Intelligent Agent project conducted by DRDC Toronto. The theory will also be applied to a UAV crew selection methodology. Also, the theory has been applied to the business rules for Multi-National Experiment 4. That is, all can view information, but only specific people have write permissions to the database. A multiple UAV interface has been designed [3] based on this framework, and will be experimented on in 2006.

- Do you have an example, closely related to the UMV situations, where the theory was implemented?

See above.

A3-5.5 REFERENCES

- [1] Powers, W.T. (1973). Behavior: the control of perception. Chicago: Aldine.
- [2] Farrell, P.S.E. (2003). Feedback in Error-correcting and Error-limiting Systems. In: Proceedings of the 50th AGM & Conference of Canadian Aeronautics and Space Institute, Montreal, Quebec, April 2003.
- [3] Forbes, K., Baker, K. and Youngson, G. (2005). Human-computer interaction between the operator and the semi-autonomous UAV team. Contract Report, DRDC Ottawa, Ottawa, Canada.

Appendix 3-6: REQUEST FOR COMMENTS ON THEORETICAL FRAMEWORKS FOR UNINHABITED MILITARY VEHICLES

Dr. Axel Schulte

A3-6.1 FORCE MULTIPLICATION

- Does the framework/model address operator to UMV ratio issues?

The framework advocated by the Munich University of the German Armed Forces, represented by Prof. Dr. Axel Schulte shall be denoted as Cognitive Automation (CA). CA as itself does not address operator to UMV ratio issues explicitly since it is a general approach towards improving system performance, to begin with. The basic idea behind CA is to mimic human performance including knowledge-based behaviour on the machine side by a knowledge-rich system incorporating explicit goals for acting, a comprehensive situation understanding and planning/problem-solving, decision-making and acting on behalf of the machine. In turn, such a cognitive system being built following an according specification, will certainly affect the operator to UMV ratio. There are several ways to introduce CA in to a work system (i.e., operator(s) controlling UMV(s)). This can be done either as cognitive assistant system, supporting the operator's work tasks by taking workload off the operator, or as an autonomously acting unit taking over certain comprehensive tasks and teaming up with the human. So, properly designed CA will supplement human teams and, thereby, bear the potential to affect operator to UMV ratio.

- If so, how could the framework/model help reduce the ratio?

If this is a goal of automation, which certainly is true in many cases, the answer is yes.

- Does the framework/model address interoperability issues?

One characteristic of CA as defined above is the explicit representation and processing of domain relevant knowledge including models for situation understanding and goals for acting. With respect to the interoperability issue, there might be distinguished between several levels of interoperability, i.e., on the low level of common protocols (e.g., Link 16) as well as on the high level of a common understanding of situations, of tasks, and of rules of engagement within situational contexts. CA, enriched by respective domain knowledge, will in principle be able to handle problems covering the full scope of these levels and, in turn, will be enabled to take over tasks from humans in a supportive or even replacing manner. Thereby, the effect of CA upon interoperability issues can be a tremendous one. Hence, the problem of knowledge elicitation and knowledge representation is still an active research issue.

- If so, how could the framework/model help improve interoperability?

To answer this question, it should be made clear, that CA is a systems engineering approach to intelligent systems design. The effectiveness of such a system is solely determined by the right ontology represented by the knowledge put in during the design process. Properly designed, we can expect a positive effect upon interoperability.

A3-6.2 UMV SCENARIOS / USE-CASES

- Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?

Simple answer, yes, since CA is a general framework. Of course, each of the mentioned domains has got it's own peculiarities. But, they all have in common, that there will be a complex dynamic situation, tactical or whatsoever, needed to be interpreted and understood, that there are goals for acting to be considered, and that there is some demand upon problem-solving and decision-making. Again, it is a matter of the kind of knowledge you put into the system, whatsoever functionality will be provided. Currently the concept has been proven in the aeronautical domain.

A3-6.3 THEORY EVALUATION

- Has the framework/model been evaluated, tested, and applied to commercial or military operations?

Yes, here is a very brief summary of activities:

- CASSY – Cockpit Assistant System: World's first comprehensive knowledge-based pilot assistant system for civil air transportation. Functional prototype successfully flight tested in 1994 with operational airline captains.
 - CAMA – Crew Assistant Military Aircraft. Follow up activity of CASSY designed for military tactical air transport missions, including tactical situation assessment and low-level flight guidance functions. Simulator tested in 1998. Flight tested in 2000 with operational German Air Force pilots. Some minor product spin-off for the A 400 M program.
 - TIMMS – Tactical Information and Mission Management System. Carries many of the CAMA ideas into the Air-to-Ground attack domain, covering operator support in an networked air warfare scenario, addressing some interoperability issues. TIMMS was simulator tested in 2000 as a functional prototype by air force pilots. Later on it was adapted to a Eurofighter cockpit avionics environment and some certification issues were addressed.
 - PILAS – Assistant system for helicopter emergency medical service mission. CA serves a general approach to the system design.
 - MiRA – Forthcoming project on Military Rotorcraft Assistant.
- Do you have an example, closely related to the UGV situations, where the theory was implemented?

Yes, currently we are working on some UAV activities, in brief:

- COSY flight – Cognitive System for the flight domain. Autonomous guidance system for a single-ship UGV mission. Project was set-up in order to prove concept of the implementation framework COSA (Cognitive System Architecture). Finished by now.
- Currently COSA is being used for the implementation of an autonomous guidance system for a multi-ship SEAD UGV mission. Main focus is the implementation of machine-machine co-operation capabilities according to the approach of CA. Will be tested in simulation.
- Development of a mini-UAV field demonstration of cognitive and co-operative capabilities on the machine side as well as intelligent operator assistance in a ground control station. The vehicles are one model-scale rotorcraft UAV and one fixed-wing.
- Manned-unmanned teaming – forthcoming project on integration of UAVs into military helicopter missions in a network centric operations context.

References to particular publications can be provided on demand.

Prof. Dr. Axel Schulte. Bath, UK. May 2005.

Appendix 3-7: REQUEST FOR COMMENTS ON THEORETICAL FRAMEWORKS FOR UNINHABITED MILITARY VEHICLES

Iain S. MacLeod

Defence College of Management and Technology
UK Defence Academy
Shrivenham

System Process/Task Organisational Model for HF V&V

A3-7.1 INTRODUCTION

The author believes that if the Task Group 017 remit is truly to be “The Human Factors of Augmenting the Force” we should produce outcomes that have enough practicality to allow their consideration applicability in augmenting force effectiveness in the ‘real’ world. For that reason I believe that the following should apply:

- Theoretical Frameworks should be formed from Theoretical Models and should have enough substance that they can be tested in reality [believe that Leiden workshop had a strong emphasis on Models].
- Following from the above, any Theoretical Model should be based on generic truth(s) underlying human systems performance in the real world [both inhabited and uninhabited] in that it can be seen to encompass any associated theoretical framework. Whilst, the use of UMVs within a network enabled community will still involve the issues of interoperability that are currently recognised [1,2] (for example, shared situational awareness, trust, the syntactic, semantic, and pragmatic), for UMVs there will be some important nuances and differences to the issues as associated with inhabited systems.
- It is likely that if a Theoretical Models are ‘true’ there will be few, maybe only one!
- A Theoretical Model architecture must address its capability to support for a Theoretical Framework architecture or architectures.
- Theoretical Frameworks are only theoretical until tested when they then become a manifestation/representation of some multi-dimensional aspect of reality.
- If a framework is to be related to reality it should consider selective combinations of Process, Context, Situation, Mission, Goal(s) [possibly both Strategic and Tactical], Force Structure, Organisations, Cultural influences, the role(s) of technology, required system functions and performance, considered level of abstraction, temporal issues, roles of personnel, jobs, teamwork, tasks, and individual actor / entity properties and activities. One example considering generic mission process associated target recognition tasks is introduced in Reference 3.
- For the considered application of any framework the prime underlying tenet(s) to be examined should be made specific, i.e., Command, control, workload, co-ordination, teamwork quality to name but a few.
- It is important that the consideration [possibly a verification and validation process] of a framework is made both statically and dynamically – statically to ensure that it is basically logical and fit for intended purpose, dynamically to examine its fit to reality. Here the role of forms of Measures of Effectiveness and Performance are important.

A required quality of human work is always associated with an understanding and acceptance of work goals, team and/or individual capabilities, appropriate skills, and a relevant knowledge plus the means to apply that knowledge within the time constraints and environments influencing the work.

A3-7.2 THE SYSTEM PROCESS / TASK ORGANISATIONAL MODEL FOR HF V&V

The System Process/Task Organisational Model for HF V&V presented at Leiden was shown using an embedded Theoretical Framework of Task Organisation. In the author's view that framework always implies levels of consideration on selected combination as discussed previously.

One of the problems in the understanding of human work is the meaningful association of theoretical interpretations [or hypothetical constructs] with a needed understanding for the application of human work practices. It is argued that the association of generic process with active practises is one avenue towards that understanding. Furthermore, derived system functions, constraints, and architecture support the quality of satisfaction of the process(es) existing to allow system capability and not necessarily a system goal. In contrast, consideration at the task level (whether that is at a higher level consideration of force/system tasks or at the level of individual human tasks) always implies a goal driven application of appropriated effort to a selection of available functions. Thus, if a system is considered dynamically it is with a task related perspective; if statically it is more at a function/constraint/architecture/required capability system perspective of consideration or the consideration of an underlying generic process. For a high level discussion on this area see Reference 3.

A3-7.3 QUESTION / RESPONSE

Considering the issues that are to be addressed with relation to the proposed theory or Theoretical Model, Table A3-7.1 gives some high level address.

THEORETICAL FRAMEWORKS

Table A3-7.1: Response of ‘System Process / Task Organisational Model for HF V&V’ to Questions

Question	Response on MODEL
Force Multiplication Does the framework/model address operator to UMV ratio issues? If so, how could the framework/model help reduce the ratio?	Yes. By allowing consideration as required through frameworks considering/evaluating issues such as Automation, Autonomy, Manning, and Personnel within the force to examine questions of force effectiveness against such as operator/UMV ratios.
Does the framework/model address interoperability issues? If so, how could the framework/model help improve interoperability?	Frameworks would need to be evolved to address specifics of interoperability and other issues. However, the model does allow for that in that the ‘Task Organisational Model’ example of a Framework within the overall model can be developed to consider the particular tenets to be examined. Interoperability is a many layered issue depending on force structure, the organisational level of the force being considered, the standardisation of procedures, and communication protocols [human and machine] to name but a few issues [1,2].
UMV Scenarios/Use-Cases Is the theory applicable to UMV situations (i.e., underwater, sea, land, air, space)?	The model is generic enough to encompass any framework considered scenario or its address through particular Use Cases.
Theory Evaluation Has the framework/model been evaluated, tested, and applied to commercial or military operations? Do you have an example, closely related to the UMV situations, where the theory was implemented?	Yes – against many, but applications mainly implicit rather than explicit. No – examples only with relation to manned systems, but within coalition operations it is possible to consider individual members of the coalition as semi autonomous and therefore to have some properties similar to UMVs.

Some forms of Framework Models (as apposed to Local Models!) already suggested can be substituted/ incorporated into the Theoretical Framework level onto the Process of the ‘System Process/Task Organisational Model for HF V&V’ Theoretical Model – examples are:

- (Perceptual) Control Theory approaches;
- Delegation using Task Hierarchy;
- Responsibility – Authority – Competency;

- Layers of Control;
- Logical/Intuitive channel model for inducing trust;
- Systems Engineering Approaches;
- Theories of agency;
- Mission Data System (software framework, goals, states and constraints); and
- Rule-based automation (recognition-primed decision-making).

It is the generating of agreed rules for applying particular Framework Models to the generic Process/Task Organisational Model that have to be formulated.

A3-7.4 AUGMENTING REALITY

Back again to real world reality – resulting from the form of Theoretical Models and Frameworks that are adopted we should decide on the form/type of scenarios, functions (plus associated performance), constraints, and capabilities of our UMV from the HF perspective. We now have to bring these into the reality of an engineering life cycle for the UMV system.

Here we should be examining the System Engineering (SE) Models and their suitability to adopt the UMV HF properties we have arrived at. All SE models are poor at considering HF at the early phase(s) of the Life Cycle (i.e., variously termed Concept/ user requirements definition/advanced studies and preliminary analysis, etc.). If HF is to become a mainstream discipline in its effects on the quality of systems design it must become part of the logical specification of system functional requirements (currently HF mainly dwells on system Constraints) and have influence on the system architecture. At the moment HF mainly dwells on attending retrospectively to the PRODUCTS of others work. Thus it is almost impossible to make an HF CASE (like a Safety Case or R&M Case) as there are no requirements to which HF can trace and show its progressive address up to system acceptance and beyond.

Some SE Standards worth a look (in the order of their greatest attention to HF) are:

- INCOSE Systems Engineering Handbook, V2, July 2000;
- IEEE 1220-1988, Standard for Application and Management of the Systems Engineering process, Full Standard version 1.0, July 27 1998; and
- ISO 15288, WD4, Life Cycle management – System life Cycle Processes, 16 February 1999.

A3-7.5 REFERENCES

- [1] Whitworth, I.R. (2005). The Systems Design Challenge of NEC. In: Proceedings of People and Systems Symposium, Institute of Electrical Engineers, London, November.
- [2] Schade, U. (2005). Towards the Edge and Beyond: The Role of Interoperability. In: Proceedings of 10th International Command and Control Research and Technology Symposium (ICCRTS), MacLean, Virginia, June.
- [3] MacLeod, I.S., Hone, G, and Smith, S. (2005). Capturing Cognitive Task Activities for Decision Making and Analysis. In: Proceedings of 10th International Command and Control Research and Technology Symposium (ICCRTS), MacLean, Virginia, June.



Chapter 4 – SYSTEM OF SYSTEMS

Chapter Lead: G. Boucek

**Contributors: G. Boucek, A. de Reus, P. Farrell, A. Goossens, D. Graeber,
B. Kovács, A. Langhorne, K. Reischel, C. Richardson, J. Roessingh,
G. Smith, P. Svenmarck, A. Tvaryanas, M. van Sijll**

4.1 INTRODUCTION

Once dismissed as novel technology that would never be useful within a dynamic environment, uninhabited military vehicles (UMVs) are being developed in greater numbers and growing sophistication as the modern military strives for greater persistence over the battlefield, more real-time intelligence, and the ability to strike heavily defended targets. New system architectures designed for interoperability are being developed to integrate multiple platforms into a common mission control element giving the war-fighter access to a large volume of real-time information. Couple that with a geographically dispersed command and control structure and the UMV operator is faced with unique challenges as traditional inner-loop control tasks are replaced with battle management and command coordination consistent with an effects based, network centric environment. The end result is an entire set of new Human Factors related challenges facing developers to ensure successful human systems integration. Resolving issues associated with connectivity, knowledge and action consistency, and transfer of control have taken center stage along with traditional Human Factors issues related to information management, information processing, decision aiding, levels of autonomy, command and control, manpower and skills, and training. To be successful, these issues must be addressed during the early stages of systems engineering to ensure proper human-centered development of UMV systems within a system-of-systems architecture.

It begins with understanding the concept-of-operation in which UMVs will operate and then identify mission system requirements. As Bruce Clough [27, Chapter 7] correctly states, “The hardest part of making a decision isn’t deciding, it’s knowing what to decide with.” What is the situation and how best can decision aiding be applied? Clough continues with another lesson learned, “Best autonomy method used is related to task to accomplish, there is no optimal method for any task.” All too often Human Factors engineers and designers try to make the leap from theory and principles directly to developing user interface concepts without a clear understanding of the operator tasks and requirements. The end result tends to be concepts that are not supported by the system architecture, or are not conducive to the real world. Following a disciplined Systems Engineering approach that combines top-down requirements development with a bottoms-up rapid prototyping capability should result in a human-centered design that is both optimal and credible. Using rapid prototyping tools that provide standard widgets, display templates, and auto-code generation allows the user interface designer to produce concepts that can be evaluated early and often by the operator as well as integrated directly with the final mission control system.

The following sections within this chapter address Human Factors issues and future research associated with human information processing and information management within the context of command and control and network centric operations. In addition, issues associated with migration of operator control and the impact on teams, interoperability, and situation awareness are discussed. The chapter concludes with a section on manpower and skills which addresses operator selection and training.

4.2 COMMAND AND CONTROL: HUMAN INFORMATION PROCESSING AND TRUST IN TIME DELAYED SYSTEMS

4.2.1 Human Information Processing (HIP) Capabilities, Limitations, and Detractors

4.2.1.1 Human Information Processing Models

Network centric capabilities interweaving sensors, humans, and decision aids will yield increases in sources and quantity of information. These advances will place heightened cognitive demands on UMV operators performing C2 tasks. The increased cognitive demands associated with a dependence on large complex data sets has been hypothesized to result in information saturation and higher levels of perceived mental workload by the National Science Foundation (NSF) and the National Research Council (NRC) [1]. The challenge is no longer the lack of information, but instead finding the required information at the right time. With the increase in available information, UMV operators performing C2 tasks will be stretched to accommodate the computational demands of complex network centric technology. To better understand the potential for overtaxing the UMV operator's cognitive capabilities a review of Human Information Processing (HIP) theory and associated supervisory control issues are presented below.

Human information processing models have been used as a framework to describe cognitive processes and characterize interactions with the environment. These models provide insight into cognitive process that occur when an individual perceives information from the environment, acts on that information, and responds to the environment [2]. The HIP models depict a sequence of serial processing stages where information from previous stages is manipulated, transformed, and/or combined with other information before passing to the next stage.

The HIP flow begins in the sensory stage when a sense organ encounters a stimulus that is within its capabilities and of sufficient intensity to initiate processing. At this stage, if attention is diverted from the stimulus, it is stored in a short-term memory store (STSS). Sensory storage is available, but is temporary and limited in terms of capacity and decay [3]. When a stimulus is attended to, it enters the perception stage where meaning is attached to its attributes to aid in detection, identification, and recognition of the stimulus (e.g., sound is detected, identified as warning, and recognized as critical). Perceptual processing occurs quickly and automatically with minimal attentional resources driven by sensory based bottom-up processing and top-down processing via long-term memory (LTM) [3]. Depending on the stimulus' attributes, either bottom-up or top-down processing may dominate. For example, when a stimulus' characteristics are ambiguous, learned rules and skills supplement the information required to identify and recognize information (e.g., radar image identified as a critical target). After perception, processed information then enters the decision making and execution stage [4]. Depending on the decision maker, task and environment, individuals may rely on different decision making processes [5]. An individual may utilize one or more means for decision making including 1) automatic, perceptual, pattern matching processes, 2) controlled, analytic decision making processes, or 3) heuristics and biases. Each of these requires the use of memory processing to gather information from LTM and actively rehearse it in working memory (WM). Once a decision has been reached, an action is selected and a motor response is executed. From the motor response, new stimuli emerge and the process begins over again creating a continuous closed feedback loop [4].

Human information processing stages are dependent on attention, and the processing that occurs following the sensory stage draws from a limited supply of attentional resources. Therefore, an individual's ability to attend to stimuli is limited and influences how information is perceived, processed, and acted upon. Information that does not receive required attentional resources will not enter consciousness. The momentary direction of one's

attention may be described in terms of selective attention. The limits of selective attention are realized when unnecessary elements of the environment are selected for processing. Although selective attention is critical in complex systems, most task environments require operators to attend to several sources of information simultaneously. A considerable amount of time sharing is needed, during which the abilities to divide attention and parallel process are essential. A prominent theory of divided attention in human task performance is the multiple resource model proposed by Kantowitz and Knight [6] and extended by Wickens [4,7,8]. The theory suggests a dimensional system of resources consisting of distinct stages of processing (encoding, central processing, and responding), sensory modalities (visual, auditory), WM processing codes (spatial, verbal), and response modalities (manual, vocal). Each dimension is thought to contain limited resources that can be distributed between and within tasks.

With respect to HIP and multiple resource models, UMV operators' cognitive workload can be described as the relationship between resource supply (HIP processing capacity) and task demand. When task demands exceed resource supply, an operator's performance decreases and mental workload is perceived. Of particular importance for UMV operator interface design is that the negative effects of workload are triggered when tasks are similar in the sensory modality, processing operations, and/or responses given by an individual [4,9,10,11]. However, when parallel processing is supported through the utilization of multiple modalities [4,12] a rich data environment can be realized, leading to a system design approach that successfully optimizes information processing, reduces workload, and maintains enhanced situational awareness in dynamic complex systems. This concept is expanded upon below with respect to leveraging user-centered design concepts in developing UMV operator interfaces to maximize information management and individual performance in C2 environments.

4.2.1.2 Environmental Stressors that Degrade Cognitive Performance

4.2.1.2.1 Impact of Provocative Environments

One of the benefits of operating in a network centric environment is that information requisite for effective C2 decision making can be supplied to UMV operators in the field. However, the environment UMV operators may be embedded in could adversely affect cognitive performance, subsequently degrading C2 decision making. In particular, environments such as surface and ground operations that induce whole body vibration, whole body motion, motion induced fatigue, and motion sickness and associated negative after effects are of concern. The critical issue is that UMV operators may be exposed to physiological stressors, such as motion sickness, that could degrade cognitive and/or fine motor skill performance with a potentially damaging affect on the attainment of a desired military effect.

With respect to whole body vibration and motion, and motion induced fatigue, the literature is inconsistent regarding their impact on cognitive C2 task performance. It is established that whole body vibration in the range from 2 – 12 Hz can effect human performance including decreased fine motor skills, fatigue, accident-proneness and health hazards [13,14,15]. However, the impact of whole body vibration is not completely clear because it is a multi-variate problem that is further compounded by individual differences [16].

Research on the impact of whole body motion on human performance has not revealed a direct relationship between provocative motion and cognitive performance, but it has established a positive relationship with motion sickness and degradation of fine motor skills [13]. Dobie [13] posits that dropout rates in whole body motion studies may indicate that individuals are capable of sustaining a high level of cognitive and general efficiency until they remove themselves from the provocative sensory environment. Research on the ability of individuals to complete C2 tasks while underway in ground vehicles shows that vehicle motion in a variety of

terrain types did not degrade cognitive performance in C2 tasks unless motion sickness resulted, in which case cognitive performance differences were found between moving and stationary conditions [17].

Motion induced fatigue is another plausible human performance detractor for UMV operators performing C2 tasks underway in ground and surface environments. The concern is that motion induced fatigue has shown a positive correlation with degraded sense of well being and lack of motivation [13]. This variant of motion induced fatigue called Sopite Syndrome, is related to motion sickness and results in individuals becoming unmotivated, drowsy, and experiencing loss of concentration resulting in task inefficiency and accident proneness that is not readily recognized by the sufferer or their supervisor(s) [13].

The important aspect to extract on whole body vibration and motion, and motion induced fatigue is that they are indirect contributors to degraded cognitive performance via motion sickness and sopite syndrome symptoms. They are also direct contributors to degraded physical abilities (e.g., fine motor skills) that may be required to manipulate an autonomous UMV C2 user interface. In addition, it has been shown that from a temporal perspective the impact of the aforementioned environmental factors on cognitive performance is linked to a step function instead of a linear function [13]. This may explain why their direct impact on cognitive performance has not been explicitly demonstrated in the empirical literature as a result of short exposure durations utilized in experimental designs. The impact of motion sickness on cognitive performance is discussed below.

Motion sickness is another example of a response to provocative environments that causes diminished cognitive and motor performance. It is plausible that UMV operators performing C2 tasks could be embedded on surface and ground platforms where seasickness and vehicle motion sickness are highly probable. With respect to seasickness rates among naval warfighters, Pethybridge [18] found in the UK Navy that 10% to 30% of naval crews suffered from seasickness during commonly experienced sea conditions and incidence rates of 50% to 90% in high sea states. The U.S. Navy's, Naval Medical Information Management Center reported that from 1980 to 1992, 489,266 new cases of motion sickness were diagnosed and 106,932 reoccurrences were recorded [13]. These figures represent a staggering loss of manpower and funds that heighten the importance of understanding the impact of seasickness on cognitive performance.

In regards to the human performance decrements associated with motion sickness, the findings are controversial depending on the type of motion sickness (chronic or acute) and the performance metrics used [19,20,21]. However, findings on chronic motion sickness in military personnel induced by sustained vestibular stimulation (e.g., motion) across multiple days revealed drowsiness, lethargy, and apathy as primary symptoms [22]. The impact of these symptoms included participants being incapacitated, refusing to perform assigned tasks, and spending a majority of their time sleeping or lying down.

Unfortunately, the use of pharmacological interventions to mitigate motion sickness introduces many problems. The efficacy and human performance decrements associated with anti-motion sickness drugs is subject to individual differences. However, the documented side effects of these drugs have been deemed unacceptable for individuals making complex operational C2 decisions, or in control of sophisticated or potentially hazardous equipment [13]. In particular, Cowings et al. [17] has shown that Promethazine (an anti-motion sickness drug), significantly degrades performance on cognitive and psychomotor tasks and decreases alertness.

While a majority of the literature on the impact of motion sickness on cognitive and fine motor skill performance has been centered on surface applications to drive ship hull design, some efforts [17] have looked at C2 operations in the ground environment using the United Defense C2V M4 vehicle (a four workstation C2

combat vehicle). Cowings et al. [17] used the C2V M4 vehicle and C2 tasks to measure performance on cognitive and motor skill tests, and motion sickness in an array of provocative, but realistic, terrains using physiological sensors and subjective reports. Seven of their eight participants reported motion sickness symptoms and composite cognitive and motor skill performance scores progressively declined during field exercises in a variety of terrains. Four of the participants indicated moderate to severe motion sickness symptoms that were not mitigated by short halts in vehicle movement. With respect to cognitive and fine motor skill performance, decrements in ability were greatest during vehicle motion and comparable to blood alcohol content (BAC) equivalencies at or above 0.08% in three participants during movement and two participants during vehicle halts.

4.2.1.2.2 Impact of Sleep Loss and Duty Cycle

Degradation of UMV operator's cognitive performance and information management capabilities in the operational environment is not limited to provocative motion, but may also arise from sleep loss and duty cycle (e.g., shift schedules). Sleep loss resulting from prolonged operations, duty cycle, and/or poor quality sleep due to motion sickness is a valid area of concern that may impact cognitive performance of UMV operators performing critical C2 tasks. Humans appear to have a limited ability to mitigate the impacts of sleep loss, but only when intrinsic motivation is sufficient, resulting in performance at pre-sleep deprived levels if wakefulness does not exceed 24 hours or the amount of sleep is greater than 50% of the individual's normal regimen [23]. The sleep loss research suggests that the relationship between sleep loss, performance and motivation is not a simple one, with motivation masking the effects of sleep loss on performance, but both motivation and performance gradually being diminished by increasing sleep deprivation. Signal [24] and Harrison and Horne [25] support the notion of sleep loss ultimately overcoming intrinsic motivation masking effects, stating that a host of cognitive skills required for decision making are reliant on the prefrontal region of the cerebral cortex, which is affected by as little as one night of sleep loss [26,27,18,29]. The skills that are affected include: attending to complex information while filtering out distractions, following a situation and recognizing the need to apply new strategies, lateral thinking and innovation, risk assessment, maintaining interest, controlling mood and behavior, the ability to self monitor performance, and the ability to communicate effectively [25]. All of the aforementioned skills are key components of effective C2 decision making in time critical situations, normal situations, and situations where normal conditions are slowly degrading.

In a network centric environment, the ability to communicate and monitor performance is critical for adding value to the network's information superiority. Autonomous UMV operators will inevitably be part of a time sensitive kill chain requiring concise communication with manned elements, and the ability to self-monitor performance is a concern from an automation bias and performance perspective (automation bias occurs when operators rely upon automated recommendations and downplay contradictory information) [30]. With respect to communication, the naturalness of speech, decoding of word meanings, and clarity of articulation have been shown to degrade with sleep loss [25]. Harrison and Horne [25] also noticed that sleep deprivation lead to increased confidence on ambiguous tasks indicating a degraded ability to self-monitor performance, which may foster automation bias when interacting with automated decision aids.

Another variable in the cognitive impact of sleep loss is the influence of the circadian system [24]. The combined effect of sleep loss and circadian rhythm produces the poorest performance at the circadian nadir [31]. The implication being that UMV operators working night shifts and experiencing sleep loss are more likely to experience performance decrements than their counterparts working a day shift [32].

4.2.1.3 The Need to Support Supervisory Control to Enhance Information Management

The sections above discuss the innate cognitive capabilities and limitations of UMV operators and how they could be decremented by the operational environment (e.g., provocative motion, sleep loss, and duty cycles), all of which is critical for designing user interface concepts that support information management in the complex C2 domain. An additional information management concern from a cognitive perspective is the need for appropriate levels of automation to support effective supervisory control and deter automation bias. Supervisory control involves an operator planning activities that are mediated by the system, implementing the plan via instructional commands to the system, monitoring the system to ensure the plan is executed, intervening when the system errs or needs assistance, and learning from the experience to understand what, why, how, and when the system took the actions it did to fulfil operator intent [32]. In information rich NCO environments, effective information management will be multi-variate in nature accounting for cognitive capabilities and limitations, environmental stressors, and appropriate levels of automation that facilitate cognition and supervisory control while avoiding automation bias pitfalls. All of these aspects are essential for supporting the use of knowledge based behaviors to complete C2 tasks involving planning, higher-level operation, and time pressured contingency interventions (e.g., time sensitive targets and system health failures). Discussed below are user-centered design operator interface concepts that show benefit for information management tasks.

4.2.1.4 References

- [1] Durlach, N.I. and Mavor, A.S. (1995). Virtual reality: Scientific and technological challenges. Washington, DC: Academic Press.
- [2] Proctor, R.W. and Van Zandt, T. (Eds). (1994). Human factors in simple and complex systems. Needham heights, MA: Allyn and Bacon.
- [3] Wickens, C.D. and Hollands, J.G. (2000). Engineering psychology and human performance (3rd ed.). Upper Saddle River: Prentice Hall.
- [4] Wickens, C.D. (1992). Engineering psychology and human performance (2nd ed.). New York: Harper Collins.
- [5] Sanders, M.M. and McCormick, E.J. (1993). Human factors in engineering and design (7th ed.). New York: McGraw-Hill.
- [6] Kantowitz, B.H. and Knight, J.L. (1976). Testing tapping time-sharing: I. Auditory secondary task. *Acta Psychologica*, 40, 343-362.
- [7] Wickens, C.D. (1980). The structure of attentional resources. In: R. Nickerson (ed.), *Attention and performance VIII* (pp. 239-257). Hillsdale, NJ: Erlbaum.
- [8] Wickens, C.D. (1984). Processing resources in attention. In: R. Parasuraman and R. Davies (eds.), *Varieties of attention* (pp. 63-101). New York: Academic Press.
- [9] Burke, M.W., Gilson, R.D. and Jagacinski, R. (1980). Multi-modal information processing for visual workload relief. *Ergonomics*, 23, 961-975.
- [10] Eberts, R. (1994). User interface design. Englewood Cliffs, NJ: Prentice Hall.

- [11] Wiener, E.L. (1987). Application of vigilance research: Rare, medium, or well done? *Human Factors*, 27, 75-90.
- [12] Samman, S.N., Stanney, K.M., Dalton, J., Ahmad, A.M., Bowers, C. and Sims, V. (2004a). Multi-modal interaction: Multi-capacity processing beyond 7 +/- 2. *Proceedings of the HFES 48th Annual Meeting*, 386-390.
- [13] Dobie, T.G. (2000). The importance of the human element in ship design. Paper presented at the Ship Structure Symposium.
- [14] von Gierke, H.E., McCloskey, K. and Albery, W.B. (1991). Military Performance in Sustained Acceleration and Vibration Environments. In: R. Gal and A.D. Mangelsdorff (Eds.) *Handbook of Military Psychology* (pp. 352-364). New York: John Wiley.
- [15] Colwell, J.L. (1989). Human Factors in the Naval Environment: A Review of Motion Sickness and Biodynamic Problems. DREA Technical Memorandum 89/220, Dartmouth: Canadian National Defence Research Establishment Atlantic.
- [16] Griffin, M.J. (1990). *Handbook of Human Vibration*. Academic Press, London.
- [17] Cowings, P.S., Toscano, W.B. and DeRoshia, C. (1998). An evaluation of the frequency and severity of motion sickness incidences in personnel within the command and control vehicle (C2V). NASA/TM-1998-112221. Springfield, VA: National Technical Information Service.
- [18] Pethybridge, R.J. (1982). Sea Sickness Incidence in Royal Navy Ships. INM Report 37/82, Institute of Naval Medicine, Gosport, England.
- [19] Abrams, C., Earl, W.K., Baker, C.H. and Buckner, D.N. (1971). Studies of the Effects of Sea Motion on Human Performance. Human Factors Research, Goleta, CA, Tech. Rep. 798-1.
- [20] Reason, J.T. and Brand, J.D. (1975). *Motion Sickness*, New York, London, San Francisco: Academic Press.
- [21] Parker, D.M. (1961). Effects of Seasickness on Error Scores in Mirror Tracing. *Journal of General Psychology*, 81, 147.
- [22] Clark, B. and Graybiel, A. (1961). Human Performance During Adaptation to Stress in Pensacola SRR. *Aerospace Med.*, 32, 93-106.
- [23] Dinges, D.F. and Kribbs, N.B. (1991). Performing while sleepy: Effects of experimentally-induced sleepiness.
- [24] Signal, T.L. (2002). Scheduled Napping on the Night Shift: Consequences for the Performance and Neurophysiological Alertness of Air Traffic Controllers. Unpublished Doctoral Dissertation. Public Health. Wellington, University of Otago.
- [25] Harrison, Y. and Horne, J.A. (2000). The impact of sleep deprivation on decision making: A review. *Journal of Experimental Psychology: Applied*, 6(3): 236-249.

- [26] Petiau, C., Harrison, Y., Delfiore, G., Degueldre, C., Luxen, A., Franck, G., Horne, J.A. and Maquet, P. (1998). Modification of fronto-temporal connectivity during a verb generation task after a 30 hour total sleep deprivation: A PET study. *Journal of Sleep Research*, 2(Supplement 2): 208.
- [27] Drummond, S.P.A., Brown, G.A., Stricker, J.L., Buxton, R.C., Wong, E.C. and Gillin, J.C. (1999). Sleep deprivation-induced reduction in cortical functioning response to serial subtraction. *NeuroReport*, 10: 3745-3748.
- [28] Drummond, S.P.A., Brown, G.A., Gillin, J.C., Stricker, J.L., Wong, E.C. and Buxton, R.C. (2000). Altered brain response to verbal learning following sleep deprivation. *Nature*, 403: 655-657.
- [29] Thomas, M., Sing, H., Belenkey, G., Holcomb, H., Mayberg, H., Dannals, R., Wagner, H., Thorne, D., Popp, K., Rowland, L., Welsh, A., Balwinski, S. and Redmond, D. (2000). Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of sleep deprivation on waking human regional brain activity. *Journal of Sleep Research*, 9: 335-352.
- [30] Mosier, K.L. and Skitka, L.J., Human Decision Makers and Automated Decision Aids: Made for Each Other? In: *Automation and Human Performance: Theory and Applications*, M. Mouloua Eds., Lawrence Erlbaum Associates, Inc. Mahwah, New Jersey, 1996, 201-220.
- [31] Van Dongen, H.P.A. and Dinges, D.F. (2000). Circadian rhythms in fatigue, alertness, and performance. In: *Principles and Practice of Sleep Medicine*. W.C. Dement, Eds. Philadelphia, W.B. Saunders Company: pp. 391-399.
- [32] Hildebrandt, G., Rohmert, W. and Rutenfraz, J. (1974). 12 & 24 H Rhythms in Error Frequency of Locomotive Drivers and the Influence of Tiredness. *International Journal of Chronobiology*, 2: 175-180.
- [33] Sheridan, T.B. (1992). *Telerobotics, Automation, and Human Supervisory Control*. Cambridge, MA: MIT Press.

4.2.2 User-Centric Information Management Concepts for Autonomous UMV Command and Control

Given the vast expanse of data that is available to UMV operators in a network centric environment, the capabilities and limitations of HIP, autonomous UMV supervisory control issues, and the impact of environmental stressors on cognitive performance, it is essential that a user-centered design of information management user interface concepts is undertaken. With respect to information management in a NCO environment the challenge is not only an abundance of data, but that information is poorly organized, represented, and displayed to the UMV operator who has to allocate attentional resources to an array of complex activities. For these reasons, systems, displays, and technologies need to be developed to aid in task execution while accommodating cognitive processing of an operator.

With respect to current UMV operators, they are often hindered by issues such as high workload and reduced situational awareness (SA) due to the complexity of the system and visual saturation [1]. To mitigate these issues, UMV operator interfaces need to be designed with an understanding of where the HIP bottlenecks occur in a task flow and present information in forms that are easily perceived, interpreted, and responded to. Several means for presenting C2 information to autonomous UMV operators is discussed below, including multi-modal interfaces, why to avoid 3D visual displays, data fusion, and decision aids.

4.2.2.1 Multi-Modal Interfaces

Traditional design strategy has focused on visual interaction and this strategy is employed in current UMV operator user interface designs [1]. In depicting information using spatial or graphical representations, visualization techniques use the human visual system to facilitate comparison, pattern recognition, change detection, and utilize various cognitive skills by the human perceptual system. These techniques have used a relatively standard set of interaction paradigms, leveraging common visual constructs such as windows, icons, menus, and direct manipulation via pointing devices (WIMPs). The pervasiveness of these paradigms provides some measure of their success, yet they are limited when a user is visually overloaded. To overcome visual saturation, designers must consider new design approaches that allow individuals to process an optimal amount of essential data. An approach discussed below leverages the auditory system in concert with the visual system because second only to the visual system, the auditory system is one of the most important and highly utilized communication channels. The ultimate goal of this visual-auditory multi-modal interface concept is to realize a holistic design that incorporates theoretically sound, principally driven multi-modal interface components that achieve a genuine symbiosis between user and system.

Instead of constraining UMV operator information management to visual interaction conventions, augmenting information via other modalities may greatly enhance HIP. One approach with great potential is to leverage the auditory paradigm of Speech, Earcons, and Auditory Spatial Signals (SEAS). The main goal of this multi-modal interaction paradigm is augmenting traditional visual interaction with auditory cues to substantially enhance cognitive information management capacity. Multiple sensory system processing can substantially improve individual information management capacity by enhancing perception, augmenting sensory processing, and speeding reaction time. Within the SEAS paradigm, the design goal is to present information in a modality that is readily perceived and in a form that is readily interpretable. A new class of multi-modal interactive systems would ensue, which would leverage available user senses, adapt to specific user's perceptual and cognitive needs, and respond to such needs by facilitating intuitive interaction with users. System characteristics can then be guided by the capabilities of human performance in terms of sensory processing (e.g., is an auditory signal loud enough to be heard), perception (can both visual and auditory stimuli be identified by user), decision making (e.g., can a user's working memory be efficiently used or is there cognitive overload), and response execution (e.g., can a user respond both manually and vocally). Based on the HIP models discussed above, a multi-modal interface can be designed that reduces mental workload, overcomes HIP bottlenecks, and optimizes human performance.

Effectively applying auditory design guidelines to autonomous UMV operator interfaces may lead to improved C2 task performance by optimally distributing information processing across human sensory systems (i.e., visual and auditory). For example, Samman et al., [2] found that participants processed nearly 3x more information when it was distributed across various sensory systems (e.g., verbal, tonal, and spatial) as compared to stimulating a single sense. In general, the empirical literature on multi-modal interfaces suggests that speech, earcons, and auditory spatial cues can be processed simultaneously with minimum interference because such information activates distinct brain regions, thereby utilizing different HIP resources.

Realizing the full potential of multi-modality means not limiting the dimensions of HIP processing to the verbal-spatial dichotomies typically associated with sensory and working memory processing codes, and extending beyond vocal-manual response modalities. The findings of Samman et al. [2,3] suggest that leveraging multi-modal sensory systems, working memory, and response modalities promotes maximum information management capacity. Within this concept, the independence of multi-modal resources can be leveraged in multi-modal interaction design to strategically utilize alternate resources at different points in operator-system interaction to streamline an operator's cognitive load. Thus, effectively designed multi-modal

SYSTEM OF SYSTEMS

displays will facilitate perception such that an operator searching a complex system can accurately detect when, what, and where in the environment relevant information is located.

To validate the utility of multi-modal interfaces for autonomous UMV C2 Samman, Jones, Stanney, and Graeber [4] implemented the interface design tenets bulleted below and adhered to speech, earcons, and spatial audio design guidelines garnered from open literature.

- Speech, earcons, and auditory spatial (SEAS) cues can be processed simultaneously with minimum interference because such information activates distinct brain regions utilized by different HIP resources.
- SEAS should exploit human's capacity to attend to a wide variety of different sound dimensions, including location, pitch, intensity, and semantic content to direct attention and enhance human information processing.
- SEAS should design parallel task processing with non-overlapping HIP resource demands.
- SEAS suggest that an individual can recall more in two tasks designed with different types of materials combined than in a single task, especially if the modalities or types of representation are very different.
- SEAS auditory displays are most appropriate for simple and short information sources.
- SEAS uses earcons, auditory icons, and data auralization to semantically map information to particular sound parameters (e.g., spectral type, rhythmic regularity, pitch, timbre, register, dynamics) or environmental sound cues to convey intended messages.

The multi-modal autonomous UMV operator interface Samman et al. [4] designed was empirically evaluated against a purely visual interface concept for C2 of UMVs. Participants were asked to complete a set of primary tasks associated with a tactical situation display where they captured radar images of targets and paired UMVs with the targets based on the required weapons for effective prosecution. Participants also completed secondary tasks associated with detection and resolution of UMV health issues. All participants completed conditions requiring control of one, two, or three groups of four UMVs where each individual UMV required supervisory control.

The general pattern of results for all of the performance metrics recorded support the concept of integrating SEAS design tenets into C2 displays. The objective of the SEAS auditory cues in this study was a reduction in operator attentional and visual perception bottlenecks, while also assessing how many autonomous UMVs a single operator could effectively control. It was hypothesized that the integration of SEAS cues would reduce perceptual bottlenecks created by a purely visual interface, thereby allowing operators to perform perceptual tasks faster and more consistently.

Overall, the results suggest that the benefits of multi-modal interfaces are realized as workload increases, particularly for secondary selective attention tasks [4]. This may be attributed to improved operator alertness levels and the opportunity to process secondary tasks and formulate an answer in parallel with primary tasks when using a multi-modal SEAS interface. In addition to gains in primary and secondary task performance, the data also revealed that subjective assessment of workload was perceived as lower with the use of the multi-modal SEAS interface than the baseline purely visual interface [4].

4.2.2.2 Three Dimensional Visualization

Three dimensional display technologies come in a variety of form factors to suit an array of applications. The assortment of 3D displays includes spatially immersive displays (SID) (e.g., domed simulators, virtual environment CAVEs), stereoscopic head-mounted displays, spatially augmented reality (SAR) displays, shutter goggles, autostereoscopic displays, and multi-layer depth displays. Intuition suggests 3D displays should afford a symbiosis between an operator and the local or remote physical environment they are working within, thereby enhancing SA and decision making. However, many studies have shown cognitive performance decrements for certain tasks when using 3D displays as compared to traditional 2D displays (e.g., God's-eye or bird's-eye views) [5,6,7,8]. These studies have shown that tasks requiring precise discrimination of relative depth or distance in the z-axis (orthogonal to the display), local surface orientation, relative curvature, relative size, distance bisection, and co-planarity are no better with 3D than with well designed 2D displays and in some cases significantly worse (relative distance, local surface orientation, relative curvature, and global orientation).

Three dimensional displays have also been shown to be sub par for information organization, a critical component of autonomous UMV operator information management. Cockburn and McKenzie [9] examined the efficacy 2D, 2 1/2 D (receding incline plane), and physical and virtual 3D models for information organization and retrieval. The results indicated performance decrements with the use of physical and virtual 3D information storage systems, suggesting there is limited use of the third dimension in information organization and retrieval tasks.

4.2.2.3 Data Fusion

Data fusion is a method for information reduction that classifies, correlates and filters sensor data to provide UMV operators a more concise picture of the battlespace [10]. Sensor data inputs are gathered from onboard (e.g., RADAR, FLIR, IFF, etc.) and offboard sources (e.g., JTIDS), then analyzed for information quality and proportionally combined to reduce ambiguity and inaccuracy. Data fusion provides UMV operators a comprehensive tactical picture that is requisite for effective battle management by fusing the data sources in a manner that operators can have high confidence in the identification and position of tracks. The power of data fusion is seen in Figure 4-1 where a tactical picture is created using un-fused and fused tracks respectively. This figure highlights the benefits of sensor data reduction whereby a visual display is created that is easier to interpret and it enhances decision making.

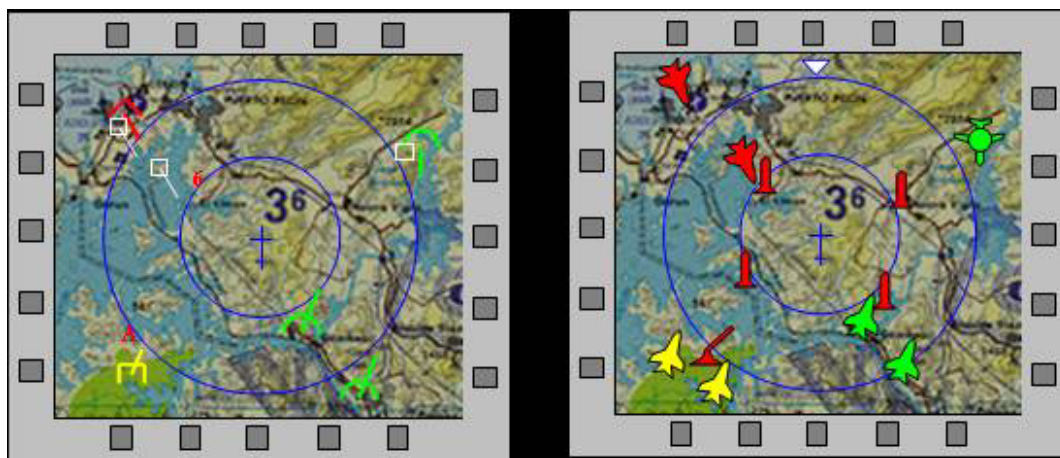


Figure 4-1: Comparison of Tactical Situation Displays with Unfused and Fused Data.

4.2.2.4 Decision Aiding

As systems grow more complex, the use of automation to help operators complete time critical human supervisory control tasks will be needed. However, Cummings [11] notes it is equally important to recognize the essential role operators play in supervisory control tasks and allocate decision making functions between humans and computers accordingly. In the C2 domain, uncertainty and time pressure are elements in the decision making process and therefore, decision aids must provide autonomous UMV operators the ability to comprehend the battlespace and how various decisions may affect the future. Cummings and Guerlain [12] suggest that decision aids for C2 applications must support knowledge-based behaviors (KBB) that require complex cognitive processing beyond application of rule based behaviors for known situations. Command and control tasks utilize KBB because the C2 environment is unscripted, open-ended and requires information integration and evaluation from a multitude of sources to form a decision in response to events in the battle space.

A key to a successful C2 decision aid for a network centric environment is the inclusion of human-computer interactive sensitivity analysis tools to determine how warfighter adjustments of decision variables could impact an overall cost function [13]. Allowing warfighters to interact with decision aids provides safety benefits, fosters SA, and permits operators minor adjustments of computer-generated solutions creating a robust system capable of flexibly responding to uncertain and unexpected events. Cummings [13] notes that a critical design element of the sensitivity analysis capability is a data presentation user interface that indicates the severity of cost function change and qualitative information regarding the impact of resource allocation shifts on the intended effect.

Another reason it is critical that operators are kept in the autonomous UMV and decision aid supervisory control loops is that U MVs are envisioned to operate in areas of uncertainty, making them subject to automation “brittleness” [13]. Automation brittleness is the concept that automated decision-support algorithms are typically fixed in code in initial design phases, and therefore unable to resolve unforeseen circumstances [14,15,16]. Higher levels of automation are ideal for rigid tasks that do not require flexibility in decision making and have a low probability of system failure [17] Conversely, higher levels of automation are not recommended for dynamic decision making environments like C2 and thus decision aids incorporating interactive sensitivity analysis are requisite because of the risks and the complexity of both the C2 domain system and the inability of decision aids to be perfectly reliable [18].

An example of a current decision aid is the Associate concept where the decision aid is able to assess the external and internal situation, make decisions based on a common view of the mission goals and plans and operator intent, and execute tasks in accordance with these goals [19,20]. As the state of the battlespace changes and data becomes available, data fusion provides a synthesized tactical picture to the autonomous U MV operator through the Information Manager (IM). The IM is responsible for deciding if and how the synthesized data will be presented to the operator. The data is also available to a Situation Assessment function along with measures of operator performance and intent gained by monitoring actions and comparing those to pre-determined plans and goals. Once a picture has been developed of the situation the Associate can make decisions based on a shared view of the mission goals [21]. Through task networks determined by comprehensive cognitive task analysis of the operator tasks in the battlefield, the Associate can determine a course of action bounded by the operator’s intent and mission goals.

The Associate concept utilizes the following four levels of authority [21]:

- Manual: The associate system may never propose a plan on its own. The operator has full control over the plan’s proposal and execution. The operator sends plans to the associate, and the associate responds like an assistant when the plan has been executed.

- **Permission:** The associate system may propose a plan, but may not activate it without explicit permission from the operator. The associate sends the proposed plan to the operator. The operator can accept or reject the plan or submit his/her own. The associate only executes plans that are commanded by the operator. After a pre-programmed time with no operator response, proposals are implicitly rejected.
- **Veto:** The associate system may propose a plan and may activate it if the plan is not explicitly rejected by the operator within a given timeframe. The associate sends the proposed plan to the operator. The operator can accept or reject the plan or submit his/her own. However, if the plan is not explicitly rejected or implicitly rejected (because the operator submitted his own plan) by the operator within the pre-programmed timeframe, the associate can execute the plan.
- **Autonomous:** The associate system may propose and activate a plan. The associate system has full control over the plan's proposal and execution. Communication is limited to the associate informing the operator after execution is complete.

Each of these authority levels can be assigned independently to the plans generated, giving the operator flexibility to choose which portions of the mission planning and tasking s/he wants the associate to undertake. Categories for assigning authority to the associate might include information management (i.e., display configuration, data transfer), mission contingency planning (i.e., attack planning), vehicle contingency planning (i.e., aircraft and systems failure), and mission plan execution (i.e., attack scripting).

The concept of an Associate is beneficial from the perspective of lowering cognitive demands utilized in decision making, however, the level of authority provided to the Associate has its trade offs with regard to supervisory control, automation bias, and automation brittleness. These are all facets of decision aids that need future research, particularly within a swarming autonomous UMV network concept.

4.2.2.5 References

- [1] Calhoun, G.L., Fontejon, J.V., Draper, M.H., Ruff, H.A. and Guilfoos, B.J. (2004). Tactile versus aural redundant alert cues for UAV control applications. Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting, 137-141.
- [2] Samman, S.N., Stanney, K.M. and Sims, V. (2004b). Multi-modal interaction: Maximizing working memory capacity. Manuscript in preparation.
- [3] Samman, S.N., Stanney, K.M., Dalton, J., Ahmad, A.M., Bowers, C. and Sims, V. (2004a). Multi-modal interaction: Multi-capacity processing beyond 7 +/- 2. Proceedings of the HFES 48th Annual Meeting, 386-390.
- [4] Samman, S.N., Jones, D., Stanney, K.M. and Graeber, D.A. (2005) Speech, Earcons, Auditory Spatial Signals (SEAS): An Auditory Multi-modal Approach. Paper presented at the HCI International Conference, July 26. Las Vegas, NV.
- [5] McGreevey, M.W. and Ellis, S.R. (1986). The effects of perspective geometry on judged direction in spatial information instruments. Human Factors, 28, 439-456.
- [6] Mazur, K.M. and Reising, J.M. (1990). The relative effectiveness of Three Visual Depth Cues in a Dynamic Air situation Display. Paper presented at the Human Factors and Ergonomics Society 41st annual meeting.

- [7] Wickens, C.D. (2000). The when and how fusing 2-D and 3-D displays for operational tasks. In: Proceeding of the IEA 2000/HFES 2000 Congress. Santa Monica, CA: Human Factors and Ergonomics Society.
- [8] Alexander, A.L. and Wickens, C.D. (2003). The effects of spatial awareness biases on maneuver choice in a cockpit display of traffic information. Retrieved March 8, 2004 from <http://www.aviation.uiuc.edu/UnitsHFD/conference/Dayton03/alexwic.pdf>
- [9] Cockburn, A. and McKenzie, B. (2001). Evaluating the effectiveness of spatial memory in 2D and 3D physical and virtual environments. Proceedings of the SIGCHI conference on Human factors in computing systems, 4(1), Minneapolis, MN, 203-210.
- [10] Pawlowski, A.M. and Stoneking, C.W. (2001). Army Aviation Fusion of Sensor-Pushed and Agent-Pulled Information. Paper presented at the American Helicopter Society 57th Annual Forum. Retrieved December 8, 2002, from <http://www.atl.external.lmco.com/overview/papers/1107.pdf>
- [11] Cummings, M.L. (2004). Automation Bias in Intelligent Time Critical Decision Support Systems. AIAA 1st Intelligent Systems Conference.
- [12] Cummings, M.L. and Guerlain, S. (2004a). An Interactive Decision Support Tool for Real-time In-flight Replanning of Autonomous Vehicles. Paper presented at the AIAA Uninhabited Unlimited Conference.
- [13] Cummings, M.L., Human Supervisory Control of Swarming Networks, 2nd Annual Swarming: Autonomous Intelligent Networked Systems Conference, June 2004. Cummings, M.L., Display Design in the F/A-18 Hornet, Ergonomics in Design (2003) Vol. 11(4).
- [14] Guerlain, S.A. (1995). Using the critiquing approach to cope with brittle expert systems. Paper presented at the Annual Meeting of the Human Factors and Ergonomics Society.
- [15] Guerlain, S. and Bullemer, P. (1996). User-initiated notification: A concept for aiding the monitoring activities of process control operators. Paper presented at the Human Factors and Ergonomics Society 40th Annual Meeting, Santa Monica, CA.
- [16] Smith, P., McCoy, E. and Layton, C. (1997). Brittleness in the design of cooperative problem-solving systems: The effects on user performance. IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans, 27, 360-371.
- [17] Endsley, M.R. and Kaber, D.B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. Ergonomics, 42(3), Gal, R. (1975). Assessment of Seasickness and Its Consequences by a Method of Peer Evaluation. Aviation. Space, Environmental Medicine, 46, 836.
- [18] Sarter, N.B. and Schroeder, B., Supporting decision making and action selection under time pressure and uncertainty: The case of in-flight icing, Human Factors, 43, 2001, 573-583.
- [19] Das, S. and Grecu, D. (2001). COGENT: Cognitive Agent to Amplify Human Perception and Cognition. Proceedings of the fourth international conference on Autonomous agents, Barcelona, Spain, 443-450. Retrieved December 8, 2002 from <http://portal.acm.org/>

- [20] Miller, C.A. and Hannen, M.D. (1999). User Acceptance of an Intelligent User Interface: A Rotorcraft Pilot's Associate Example. Retrieved December 8, 2002 from <http://www.iuiconf.org/99pdf/1999-001-0020.pdf>
- [21] Elmore, W.K., Dunlop, R.D. and Campbell, R.H. (2001). Features of a Distributed Intelligent Architecture for Uninhabited Air Vehicle Operations. Paper presented at the proceedings for of the AUVSI Uninhabited Vehicles 2001 Symposium. Retrieved December 8, 2002 from <http://www.asinc.com/pdfs/auvsi2001-architecture.pdf>

4.2.3 Trust in Time Delayed Systems

4.2.3.1 UMV and Time Delays

4.2.3.1.1 *Notions of Time Delays*

The operative context of UMV is characterized by their complex dynamic environment. In such situations, control is not total. Indeed, the operator's actions are combined with the process dynamic and he is not alone in this process [1]. Therefore, the environment in which he is acting leads him to update, according to the context, his mental representation of the system. The operator's lack of action is equal to a change in the problem to solve. This kind of environment makes more critical the management of UMVs because this system presents important time delays; cognitive needs introduced by the evolving aspects of the environment are thus associated with latency.

The concept of time delay gathers a certain number of subdivisions (Figure 4-2). We can define a response delay, an information delay and a feedback delay. Each of them has a specific influence on the conduct of robotic systems.

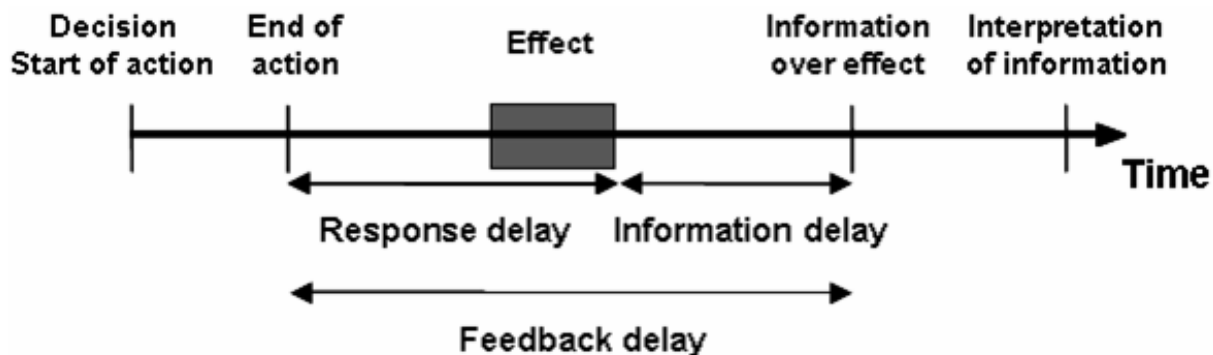


Figure 4-2: Time Delays.

A response delay is the lag between the action and its effect on the controlled variable [1]. It is under the influence not only of automation, but also of actions (nature, time and sequence of execution). Indeed, from the operator's point of view, an information delay (time delayed information over the effect) can be added by itself to the response delay. A too long information delay will lead to decrease for the operator in observing his own actions effect. Also, it makes the mental evaluation of the plan making toward a specific goal more difficult [2]. The difficulty of observing the cycle "information gathering-diagnosis-action-evaluation of actions" all in one makes the building of mental representation of the process evolution more

complicated [3]. In this case, the operator must hypothesize the current state of the system in order to make decisions and corrects it according to his results. However, a slick anticipation may be obviously not very relevant, in situations where uncontrolled factors can interfere with the actions effects. With these difficulties, one found an extra error production. Indeed, Ferrel [4] shows in a tele-operation task, that the presence of information delay increases the production of errors (59% of errors made versus 6% in non time delayed conditions).

Information over the process given to the operator is not always synchronised with events, but can be produced with some time delay. The feedback delay, or latency, is thus the sum of the response delay and the information delay. We notice an obvious deterioration of performance when time delay happens, because of the lack of synchronization between the operator's time and the process time. In practical, we note, in a technological context, that it is not possible to reduce latency to zero: Moreover, one will be careful for this latency to be either constant, or equal for all sensorial feedbacks, and inferior to a critical threshold [5].

The nervous system itself, have some time delays in the visual-motor loop. Nature has developed some processes allowing us to forecast the consequences of our actions and thus to anticipate the sensorial feedback up to a certain level. With regard to visual information, Keele and Posner [6] have estimated this threshold at 200 ms. In best cases, these predictive mechanisms allow us to compensate latency until a threshold of 250 ms: any time delay higher than this value damage the performance. Nevertheless, over this crucial threshold, operators show a certain form of adaptation to time delays by using specific strategies allowing them to reach a certain performance in their activity, while accepting a lowering system dynamics.

4.2.3.2 Move and Wait, a Strategy Facing Time Delays

With time delays, operators develop some strategies allowing them to fulfil their aim. So, they seem to adopt on their own initiative, and spontaneously, a "Move and Wait" strategy (MaW), i.e., they act, wait for the feedback (in general a visual one) before beginning a new move. This strategy allows operators to limit the incoming of unstable and unwanted movements [7], but without excluding them. In return, the task is considered, by the operator, as divided into various intermediary goals [4]; the fluidity of the movement is then particularly affected. The activity is no longer considered as a whole, but like a succession of given actions. Consequently, we notice a linear relation between the completion time and the intensity of time delay, and this, even for complex and time consuming tasks [8]; the main effect being due to the wait for feedbacks.

Beneath 0.2 s of time delay, operators do not seem to be obliged to use the MaW to obtain good results. Beyond this value, not applying this strategy compels the operator to provoke an oscillation of the system. Indeed, the late perception of system responses leads the operator to modify his instruction (most of the time by amplifying it). The operator, noticing that this action is over dimensioned will configure an opposite instruction which will be in itself amplified. And thus, this process will oscillate and diverge.

While most of the beginners have jerky non-coordinate and over amplified movements, training leads to "smooth" movement. In fact, the training modifies the quality of concerned representations, in order to make them more flexible in the action at a given moment. So, we notice a smoothing of the imperfections, with the coming of a strategy of delayed feedbacks: the operator makes a certain number of actions without waiting for feedbacks (MoveS and Wait). This use of delayed feedbacks shows some characteristics:

- It shows up after a great number of trials.
- It is rather the exception than the rule.

- It's only use during in mastered activity (trust in the system).
- The operator doesn't try to predict the position or the velocity of its actions, but only the success or the failure of the action.

4.2.3.3 Visual Perception and Time Delays

The visual perception, through artificial sensors, is one of the main means to extract from the environment the necessary elements to a decision-making. It allows evolving UMV order. Yet, the operator must use remote artificial vision systems and therefore through a dissociation between visual space and action space. This involves a reduction of environmental clues resulting from the contraction of the visual field, and then tends to make the perception of the action space complicated [9]. The presence of the screen provokes by itself a change in the control space [10]. This perceptive activity can be described by the completion of two distinct tasks: the exploration of the environment and the search for targets within a visual scene delimited by a sensor field. As far as this first task is concerned with those feedback delays, we note a similar behaviour in tele-operation tasks. So we find again negative effect of time delay in exploration; performance decreases through a linear function with time delay. Consequently, going down to 2.5s of time delay, we notice that performance reduces by 50% [11].

Added to these problems, we found certain alterations of the perceptive mechanisms implicated in visual research. Indeed, according to the Features Integration Theory [12,13] various strategies can be brought into action with this type of activity. However, with time delays, only a serial features conjunction mode is chosen (sequentially attention based process of exploration which is very expensive in cognition and not very fast) [14]. This choice will lead to a compromise produced by a central mechanism of management [15] between cost, performance and trust associated with a given strategy.

Being in a downgraded situation will tend to select a strong and statistically sure mode in order to carry out this task of targets research. This choice is made in spite of being costly. Indeed, a non detection becomes critical in cases of strong time delays; the cost of new research initialization becomes too important compared with a serial exploration. Two mechanisms can be at the origin of this behaviour. First, fear of an incorrect and ineffective realization of the task, creates certain anticipation based on previous experiments. Thus, the waste of time from a non detection is foreseen by the operator. He selects, consciously, this mode of research in order to prevent this kind of incidents. Second, a cognitive control/regulation mechanism would carry out during the activity a cost evaluation of the tasks realization. This last would involve the creation of a feeling of difficulty, with the consciousness of loosing control of the situation, i.e., a "failing risk of the cognitive capacities because of the saturation of the cognitive resources" [16]. This consciousness leads the operator to select a strong serial features conjunction mode in order to reduce this feeling of difficulty.

From a certain control, it becomes possible to release some resources from the time delays management to prevent a "cognitive overload", and thus to restore a certain confidence in the system. From this confidence is restored, the acquisition of new research mode would be possible. A redistribution of additional resources towards other tasks is then possible. This implies that the use of research mode strongly depends on the existence of a free resources span. The reduction of this last (starting with one second of time delay) involves the impossibility of more powerful research modes "choice".

Time delays in a multi-tasks system involve quickly a cognitive capacities overload, and thus induce a change of strategies used in the realization of the activity. We note the use of MaW, with regard to the exploration of the environment, or the inhibition of powerful perceptive mechanisms of visual research. These facts bring the operator to wonder about his self-confidence and the trust in the system. This questioning is the result of

uncertainties due to system time delays, involving difficulties of representation and thus of understanding the situation.

4.2.3.4 References

- [1] Hoc, J.-M. (1996). Supervision et contrôle de processus: la cognition en situation dynamique. Presses universitaires de Grenoble, Grenoble.
- [2] Decortis, F. (1992). Processus cognitifs de résolution d'incidents spécifiés et peu spécifiés en relation avec un modèle théorique. thèse, Université de Liège, Belgique.
- [3] De Keyser, V. (1991). Temporal reasoning in continuous processes: segmentation and temporal reference systems. Paper presented at the third European conference on Cognitive Science approaches to Process Control. Cardiff, September.
- [4] Ferrell, W.R. (1965). Remote manipulation with transmission delay. IEEE Transactions on Human Factors in Electronics HFE-6 (1).
- [5] Ferrell, W.R. (1965). Remote manipulation with transmission delay. IEEE Transactions on Human Factors in Electronics HFE-6 (1).
- [6] Keele, S.W. and Posner, M.I. (1968). Processing in visual feedback in rapid movement. Journal of Experimental Psychology, 77, 155-158.
- [7] Sheridan, T.B. and Ferrell, W.R. (1963). Remote manipulation control with transmission delay. IEEE Transactions on human factors in electronics, HFE-4, 25-59.
- [8] Ferrell, W.R. and Sheridan, T.B. (1966). Supervisory control remote manipulation. IEEE Nerem record, Northeast electronic research and engineering meeting November 2, 16-17. Boston.
- [9] Massimo, M. and Sheridan, T.B. (1989). Variable force and visual feedback effects and teleoperator man/machine performance. Proceedings of NASA conference on space telerobotics, 31-01/31-02. Pasadena.
- [10] Yates, J. and Orlikowski, W.J. (2001). Genre systems: Chronos and Kairos in communicative interaction. In: Coe, R., Lingard, L, and Teslenko, T. (Eds), The Rhetoric and Ideology of Genre: Strategies for Stability and Change, Hampton, Cresskill, NJ, pp. 103-21.
- [11] Kovács, B., Chalandon, X. and Amalberti, R. (2005-1). Etude des dégradations temporelles en situation dynamique: application aux UxAV. To be published.
- [12] Treisman, A. (1999). Feature binding, attention and object perception. In: G. W. Humphreys, J. Duncan, and A. Treisman (Eds.) Attention, Space and Action: study in Cognitive Neuroscience. Oxford University Press, 1999.
- [13] Treisman, A. and Gelade, G. (1980). "A feature integration theory of attention", Cognitive Psychology, 12, 97-136.
- [14] Kovács, B., Amalberti, R. and Chalandon, X. (2005-2). Recherche visuelle en situations de dégradations temporelles. To be published.

- [15] Kahneman, D. (1973). *Attention and Effort*, Englewood Cliffs, NJ: Prentice Hall.
- [16] Amalberti, R. (1996). *La conduite de systèmes à risques*. Presses universitaires de France, Paris.

4.2.4 Uninhabited Military Vehicles and Trust

4.2.4.1 Time Delays and Representations

The UMV system with all the inherent time delays creates spatial and temporal uncertainties for the operators. This means that real time reaction is not possible [1]. Keren and Roelofsma [2] suggest that uncertainty and time delays affect the decisions through only one common dimension. Time delays eliminate the effect of certainty such as uncertainty would do, because time delays carries part of risk, which leads to uncertainty. The problem arises from dissociation between the operator's universe and the UMV universe. The more important this variation is, the more it is difficult to synchronize process time and operator's time. This involves great difficulties in answers adjustment, which must be relevant with the time sequences of the environment. The operator encounter two linked difficulties in this process, to adapt the production of commands in due time, and to build and maintain a representation of the system in a temporal and implicitly spatial scale because of the environment dynamics. The cognitive requirements related to the UMV management are fulfilled by the creation of an internal representation of the system, its evolution, and the action plans. This represents more or less the reality and depends on the nature of the external representations [3], which can be considered as the primary support of the activity. Their informational levels are directly associated with the quality of the operator's internal representation. Thus, the simpler the operator's system model is, the closer the feedbacks must be to reach an acceptable level of performance. The more distant feedbacks are, the less the operations on these mental representations are able to work, and the more the model needs other regulations such as anticipations. Paradoxically, anticipations require relatively powerful system of internal and external representation.

Time delays in a system leads to some difficulties of building and maintain relevant mental representations with respect to a given objective.

4.2.4.2 Representation and Understanding

The representation of the world allows its understanding. However, the knowledge by itself of the system in its environment cannot fully satisfy understanding. Indeed, understanding is not a property of environments; there is no understanding without an intention which directs the analysis and building of relations on a limited part of the environment components [4]. Thus, intention and understanding are closely linked: understanding a situation consists in building a coherent representation of the world for the goal to achieve and, to update it to satisfy the evolving requirements of this universe. The difficulty of understanding the situation comes from the weak quality of the system representation. Creating consistency between past, current, and future events and the operator's intentions is complex. The lack of predictability leads to a restriction of anticipations, a short-term control, a permanent high workload [4,5,6], and an increased need for confidence [7]. Problems related to the building of an operative system representation in an environment, leads to a progressive loss for the operator's understanding over his controlled/supervised system.

4.2.4.3 Understanding and Trust

In the case of UMV, the symbolic intermediaries create, for the operator, a certain representation of the world [8]. This synthetic view of the reality raises the question of trust in the system. Indeed, information for the

operator presents some specific deformations of the vehicle environment (be it wanted or not). Then, the understanding of the situation depends of the consistency, towards a given intention, of the external representation of the world provided by the system, and the world itself. The ease and stability of this relation are directly related to the quality and the speed of trust acquisition. Well, the temporal gap between action and his effect tends to increase the uncertainty and then the need for trust [9,10].

Trust can be defined as “the attitude that an agent will help achieves an individual’s goals in a situation characterized by uncertainty and vulnerability” [11]. In the case of a decision aid, trust is “... the extent to which a user is confident in, and willing to act on the basis of the recommendations, actions, and decisions of an artificially intelligent agent” [12]. This can be determined by a stake with a probability of an adverse outcome [13]. Two different notions can define trust: self confidence (egocentric) and trust in the system (exocentric). It is their ratio which indicates the level of acceptable risk (internal and external) for the operator. Then, we can consider trust like a risk which is accepted to prevent other risks [4].

4.2.4.3.1 *Trust: a Regulator of the Cognitive Compromise*

The operator confidence seems to evolve with the mechanisms of acquisition and particularization of his know-how [14]; the ease for detecting the behaviour of the system and its supporting state indicators increase this confidence [15]. When confident, the operator tends to automate certain specific know-how with regards of his task. This behaviour, associated with a certain simplification and loss of flexibility of the system management, structures and facilitates the causal analysis. The operator makes “more” (in term of performance) with “less” (in term of knowledge) [4]. However, the flexibility of adaptation to the context, resulting from confidence, cannot be directly associated with the know-how. Indeed, confidence is more related to an “ability of management” than with a know-how control. The degree of confidence in a system allows the operator to explore a more or less wide field of his cognitive compromise with respect to certain know-how, and then allows him to increase his possibility of actions on the situation. This flexibility of the cognitive compromise authorizes, from time to time, the operator to take more risks (a lower control) in exchange of a greater adaptability in his task. This risky behaviour obeys to a principle of homeostasis, in accordance with the modification of the environment [16]. Then, we can define a judgement of confidence like a metacognitive activity [17,18,19]; confidence is a regulator of the operator’s level of control. In the case of a low confidence, the operator tends to select a conscious and logical control mode based on his metaknowledge, which is associated with a great workload. On the contrary, a high confidence involves a reduction of the level of control, with an increasing production of routine errors in the case of overconfidence [4,13].

4.2.4.3.2 *Trust and Automation*

Confidence of an operator in an automated system determines its behaviour toward the system [20,11,21,7]. Lee and Moray [22] suggest that operators use automatic modes in accordance to their previous level of confidence, the probability of failures and their skills in manual control. Decisions to switch over from one mode of command to another can be predicted by the ratio between the level of confidence in the system and the operator’s self-confidence [23,24,25]. Therefore, the choice of a manual control shows a confidence in the manual mode better than in automation. This choice is made on a subjective evaluation of the reliability of the system and on the own skills of the operator. Indeed, an operator will not use a reliable automatic system if he does not trust it. However, in the case of system which presents failures, the operator can judge his own capacity to manage it manually less reliable and riskier than in an automatic mode due to workload increase [26,27]. Then, the operator prefers to switch to an automatic mode while reinforcing his level of supervision. This can be confirmed by the fact that the level of detection of failures by the operator varies conversely with the reliability of automation [28].

In the first interaction, we note, without failures, a quick raise of a(n) (over)confidence of the operator towards the system [29] especially in the case where decisions are taken from visual information [17]. This confidence remains until important failures happen. Indeed, occasional failures do not induce a change of the control mode as long as these are bearable for the operator with a lower cost in mental workload. Nevertheless, Lee and Moray [22] have shown that whatever problems encountered confidence in automation settles slower than it decreases.

We note that certain researchers consider that man, in his interaction with an artificial system, reproduces the same behaviours of management of trust as those observed in social situations between individuals [30,31,32,33] and this in spite of the fact that technological artefacts do not have motivations. These researchers talk even about “personality” of the system [34] and about its links with the operator’s personality.

4.2.4.4 Conclusions

The difficulties (exploration of the environment and visual searches) associated with time delays lead the operator to reconsider his confidence about the system, often with a negative view. It’s not in favour of a strict control by the operator, but rather for supervision and task sharing between the operator and the system. Nevertheless, we have to be careful to not impoverish the operator’s activity and then consequently his understanding of the process. In the context of a hermetic system (for the operator), the activity of supervision tends to decrease. Indeed, the use of automation and then the difficulty of control are associated, in a timely manner, with a reduction of skills and the ability to supervise the system [35]. Recovery of errors by the operator is then particularly affected.

With these problems must be added risks about the implication of the operator towards the UMV in his control/supervision. Indeed, spatial and temporal distance between the command station and the aircraft lead the operator in a no interpretation status of the bonds between these two entities. Thus, the intermediary space between these two entities is considered like a black box where the outputs do not seem to be related to the inputs of the operator. This space tends to be an independent operative intermediary between the operator and the UMV. This creates a gap between these two entities which move in two different spatial and temporal universes, and then leads the operator to work only in the universe which can be directly controlled. Then, the operator will consider his task only toward an external artificial representation of the UMV (the screen in the command station) and not in relation to a real, and distant, massive aircraft.

4.2.4.5 References

- [1] Gilson, R., Richardson, C. and Mouloua, M. (1998). Key human factors issues for UAV/UCAV mission success. AUVSI’98, 1998.
- [2] Keren, G. and Roelofsma, P. (1995). Immediacy and certainty in intemporal choice. *Organizational Behavior and Human Decision Processes*, 63, 287-297.
- [3] Mailles, S. (1996). Les représentations analogiques comme support de l’anticipation dans les environnements dynamiques. Thèse de Doctorat Nouveau Régime, Université Toulouse-Le-Mirail, Toulouse.
- [4] Amalberti, R. (1996). La conduite de systèmes à risques. Presses universitaires de France, Paris.
- [5] Yates, J. and Orlikowski, W.J. (2002). Genre systems: Structuring interactions through communicative norms. *Journal of Business Communication*, 39(1), pp. 13-35.

- [6] Javaux, D. and De Keyser, V. (1994). Complexité et conscience de la situation, Aides au contrôle de processus dynamiques, In: R. Amalberti (Dir.), Briefings, IFSA-Dédale, Paris.
- [7] Parasuraman, R. and Riley, V. (1997). Humans and automation: Use, misuse, Disuse, abuse. *Human Factors*, 1997, 39(2), 230-253.
- [8] Weill-Fassina, A. (1979). Présentation spatiale des données de travail et traitement des informations. Point de vue et hypothèse, *Psychologie Française*, 24 (3-4), 205-227.
- [9] Giddens, A. (1990). *The consequences of modernity*. Stanford University Press, Stanford.
- [10] Brynjolfsson, E. and Smith, M. (2000). Frictionless commerce? A comparison of internet and conventional retailers. *Management Science* 46 (4), 563-585.
- [11] Lee, J.D. and See, K.A. (2004). Trust in automation: Designing for appropriate reliance. *Human Factors*, 2004, 46(1), 50-80.
- [12] Madsen, M. and Gregor, S. (2000). *Measuring Human-Computer Trust*. Gladstone, Australia, Central Queensland University; 12.
- [13] Riegelsberger, J., Sasse, M.A. and McCarthy, D. (2005). The mechanics of trust: A framework for research and design. *Int. J. Human Computer Studies*, 2005, 62, 381-422.
- [14] Amalberti, R. (1994). Briefings, IFSA-Dédale, Paris.
- [15] Molloy, R. and Parasuraman, R. (1994). Automation-induced monitoring inefficiency: The role of display integration and redundant color coding. In: M. Mouloua and R. Parasuraman (Eds.), *Human performance in automated systems: Current research and trends*, 224-228. Hillsdale, NJ: Erlbaum.
- [16] Burke, J.L., Murphy, R.R., Coovert, M.D. and Riddle, D.L. (2004). Moonlight in Miami: an ethnographic study of human-robot interaction in the context of an urban search and rescue disaster response training exercise. *Human-Computer Interaction*, 19(1&2), 85-116.
- [17] Gaillard, J.-P., Freard, D., Colle, E. and Hoppenot, P. (2003). Operator's self confidence to detect mobile robot trajectory errors. *Le travail Humain*, 2003, 66 (1), 1-21.
- [18] Valot, C. and Amalberti, R. (1992). Metaknowledge for time and reliability, *reliability Engineering and Systems Safety*, 36, 199-206.
- [19] Valot, C., Grau, J.-Y. and Amalberti, R. (1993). Les métaconnaissances: une représentation de ses propres connaissances, In: A. Weill-Fassina, P. Rabardel, D. Dubois (Eds.), *représentations pour l'action*, Octarès, Marseille, 271-293.
- [20] Itoh, M., Abe, G. and Tanaka, K. (1999). Trust in and use of automation: Their dependence on occurrence patterns of malfunctions. In: *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, Vol. 3, 715-720. Piscataway, NJ: IEEE.
- [21] Muir, B.M. (1994). Trust in automation: 1, Theoretical issues in the study of trust and human intervention in automated systems. *Ergonomics*, 1994, 37, 1905-1922.

- [22] Lee, J.D. and Moray, N. (1992). Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35, 1243-1270.
- [23] Lee, J.D. and Moray, N. (1994). Trust, self-confidence, and operator's adaptation to automation. *International Journal of Human-Computer Studies*, 40, 153-184.
- [24] Moray, N., Hiskes, D., Lee, J. and Muir, B. (1995). Trust and human intervention in automated systems. In: J.-M. Hoc, P.C. Cacciabue, and E. Hollnagel (Eds.), *Expertise and technology: cognition and human computer cooperation*. 183-194. Hove, UK: Laurence Erlbaum Associates Publishers.
- [25] Parasuraman, R. and Mouloua, M. (1996). *Automation and human performance: Theory and applications*. Hillsdale, NJ: Erlbaum.
- [26] Parasuraman, R., Molloy, R. and Singh, I.L. (1993). Performance consequences of automation-induced "complacency". *International Journal of Aviation Psychology*, 3, 1-23.
- [27] Riley, V. (1994). Human use of automation. Unpublished doctoral dissertation, University of Minnesota.
- [28] May, P., Molloy, R. and Parasuraman, R. (1993). Effects of automation reliability and failure rate on monitoring performance in a multitask environment. Paper presented at the Annual Meeting of the Human Factors Society, Seattle, WA.
- [29] Kahneman, D., Slovic, P. and Tversky, A. (1982). *Judgement under uncertainty: Heuristics and Biases*, Cambridge University Press, Cambridge.
- [30] Falzon, P., Amalberti, R. and Carbonell, N. (1986). Dialogue control strategies in oral communication, Hopper and Newman (Eds.), Amsterdam, Elsevier, 73-98.
- [31] Fogg, B.J. (2003). *Persuasive technology. Using Computers to change what we think and do*. Morgan Kaufmann, San Francisco, CA.
- [32] Lehner, P. (1987). Cognitive factors in user expert-system interaction, *Human factors*, 29 (1), 97-109.
- [33] Reeves, B. and Nass, C. (1996). *The media equation: How people treat computers, television, and new media like real people and places*. CSLI Publications, Stanford.
- [34] Cook, J. and Savendy, G. (1989). Perception of computer dialogue personality: an exploratory study, *Int. Journal Man-Machine Studies*, 31, 717-728.
- [35] Bainbridge, L. (1987). Ironies of automation. In: J. Rasmussen, J. Duncan, and J. Leplat (Eds.), *New Technology and Human Errors*, NY, Wiley, 271-284.

4.2.5 Future Research

As knowledge, technology, and autonomous UMV system capabilities progress, HSI research efforts must also continue to address user-centered design aspects of information management for C2. Five pertinent areas of enabling technology research are discussed below, including, multi-modal user interfaces, augmented cognition, collaborative tools, chat applications, and supervisory control of autonomous UMV swarms. See the "Advanced UMV Operator Interfaces" chapter within this publication for additional design concepts.

4.2.5.1 Multi-Modal Interfaces

Continued multi-modal interface research is needed to further understand HIP and how best to leverage cognitive resource and attention pools utilized in processing sensory inputs, decision making, and response execution. The concern is that HIP benefits from presenting information multi-modally could be tempered if the costs for modality coupling and switching are high. Another vein of research is an examination of the potential benefits of multi-modal interfaces to mitigate the effects of visually induced motion sickness in provocative environments while allowing the operator to remain effective in performing C2 tasks. Multi-modal user interface research should also investigate the potential for supporting reduced manning concepts and personnel selection criteria for effective use of multi-modal systems. Finally, in conjunction with a deeper understanding of how multi-modal interfaces leverage HIP concepts, research should also be undertaken to compliment the augmented cognition concept discussed below. In particular, the creation of modality based user interface augmentation guidelines for cognitive bottleneck resolution in response to real time assessment of operator workload and the HIP resources overburdened.

4.2.5.2 Augmented Cognition

Augmented cognition is a neuroergonomics enabling technology concept that leverages HIP models, user interface augmentation concepts founded in HIP theory (e.g., multi-modal user interfaces), and physiological sensor technologies. The goal of augmented cognition is to develop a cognitive feedback loop between operator and system that allows the system to sense when an operator is experiencing unacceptable levels of cognitive workload, mental fatigue, and/or stress. When the aforementioned contributors to cognitive performance decrement are detected, an augmentation manager appropriately alters the user interface or information presentation modality to mitigate cognitive performance decrements.

From an applied perspective, the goal of augmented cognition is to increase the amount of information that operators can process and utilize in decision making, reduce manpower requirements, and improve selective attention during stressful battlefield conditions. These applied goals are related to autonomous UMV C2 by directly impacting the number of automated U MVs an operator can control and providing an effective means for enhancing cognitive processing and information management. Augmented cognition research efforts relating to autonomous U MV C2 [1] have utilized a suite of physiological sensors (pupil size, EEG, ECG, EOG, EMG, and functional near infrared (fNIR)) and statistical process control techniques to assess an operator's cognitive state, while employing an array of user interface augmentations to mitigate high cognitive workload contributors. Barker [1] conducted a series of experiments to address cognitive bottlenecks in working memory, executive function, sensory input, attention, and response generation. The experiment results demonstrate that aiding from closed-loop augmented cognition significantly improves autonomous U MV operator performance on both primary and secondary C2 tasks. The primary tasks that showed improvement were associated with ingress and attack phases for suppression of enemy air defences (SEAD) mission where the operator was controlling one, two, or three strike packages consisting of four U MVs. The secondary tasks that showed improvement were detecting and responding to vehicle health alerts.

While research in the domain of augmented cognition is based on a solid theoretical foundation, substantial work remains to validate the efficacy of the concept at both basic and applied levels. Future research is also required to improve physiological sensor capabilities, packaging, and optimal placement. In conjunction with sensor development is the improvement of techniques for processing the sensor data and selection of appropriate user interface augmentations. Augmented cognition is a promising concept that could be an enabling technology breakthrough for autonomous U MV C2 as the associated body of knowledge continues to expand and mature.

4.2.5.3 Chat Applications

The use of chat applications and instant messaging were discussed above as potential tools to enhance a variety of collaborative C2 scenarios. They are revisited in this section because they may result in an unexpected consequence of the convergence of network centric technical capabilities and societal trends. Cummings and Guerlain [2] used chat during a decision aid study as an operationally valid secondary task to measure workload. Unexpectedly, they found that the chat application and the information contained in the chat messages dominated operator attention allocation while performing time sensitive retargeting of tactical tomahawk missiles. Cummings and Guerlain's [2] intent was to create a realistic secondary task that required spatial reasoning skills in a chat application that was familiar to naval personnel. The chat application conveyed messages containing basic information about missile status, instructions for action, or queries for information from superiors about past, present, and future elements of missile and target status. Interestingly, Cummings and Guerlain's [2,3] found that participants became fixated on the chat application despite explicit instructions that time critical retargeting was the highest priority task and answering chat queries was the lowest priority task. In addition, participants were told that incoming chat messages were generated by a scripted computer program and their responses were not being read by a human. In spite of stressing instructions to only attend to chat when no other tasks were occurring, many participants responded to chat queries before attending to the more pressing time sensitive target problems. Cummings and Guerlain [2,3] suggest that the over-attention to the chat application degraded the overall task performance of some participants, which could have costly operational consequences.

The findings of Cummings and Guerlain [2,3] indicate future research may be needed to understand the predilections of an e-enabled warfighter population that regularly uses social connectedness applications, such as chat and IM, in their work and personal lives. Inevitably, current and future warfighters responsible for C2 of UMVs will bring with them generational culture biases where compelling personal connections are established via e-enabled medium. As network centric technical capabilities evolve and incorporate common place commercial applications, future research should be directed at understanding the societal impact of these technologies on the military community and the possible impact on training, tactics, and procedures as well as warfighter performance.

4.2.5.4 Decision Aiding for Autonomous UMV Swarm Control

Autonomous swarming UMV networks will create new aspects of operator decision making complexity in C2. One of the primary advantages of autonomous UMV swarming networks is the ability to process large amounts of sensor data in short periods of time to optimally achieve an intended effect. Humans will continue to be needed in autonomous swarm networks to ensure safety and monitor progress toward an intended effect as part of the supervisory control and decision making loops. However, Cummings [4] notes that because of the revolutionary nature of swarming technology, futuristic operator interaction with complex autonomous UMV swarms is not well understood, and more research emphasis needs to be placed on operator requirements, strengths, and limitations for supervisory control. Cummings [4] suggests that future research in this domain should include an investigation of the interaction of increasing vehicle autonomy on human supervisory control, the effect of increased levels of automation in decision-making, and how situation awareness is affected by increasing levels of vehicle autonomy and automated decision making. The crux of the future research issue is to devise an autonomous UMV swarm – operator feedback loop that allows the operator to understand what, how, and why a swarm behaves like it does [4].

While current and past research has focused on determining levels of automation that promote effective operator-system interaction [5,6,7,8,9,10], little has focused on the C2 domain, and virtually no research has been done on operator-autonomous swarm interaction. Cummings [4] notes that with the creation of

autonomous UMV swarm networks that communicate with both humans and each other, the supervisory control problem space increases in scope and complexity. From a future operator decision aid design perspective, the implication is that it will be paramount to determine the impact of automation levels for decision making, the effects of different collaboration levels between UMGs, the interactions between the two automated systems (i.e., decision aids and swarming UMG networks), and how best to represent to the operator multi-objective cost functions that should either be minimized or maximized [4]. From a high level perspective, future research on supervisory control and operator decision aids for autonomous UMG swarms should focus on the impact of increasing vehicle autonomy on supervisory control, the effect of increased levels of automation in decision making, and how situation awareness is affected by the increasing levels of UMG autonomy and decision making automation Cummings [4].

4.2.5.5 References

- [1] Barker, R. (2005). The Boeing Team Fundamentals of Augmented Cognition. Paper presented at HCI International, July 25th. Las Vegas, NV.
- [2] Cummings, M.L. and Guerlain, S. (2004a). An Interactive Decision Support Tool for Real-time In-flight Replanning of Autonomous Vehicles. Paper presented at the AIAA Uninhabited Unlimited Conference.
- [3] Cummings, M.L. and Guerlain, S., Using a Chat Interface as an Embedded Secondary Tasking Tool, 2nd Annual Human Performance, Situation Awareness, and Automation conference, March 2004.
- [4] Cummings, M.L., Human Supervisory Control of Swarming Networks, 2nd Annual Swarming: Autonomous Intelligent Networked Systems Conference, June 2004. Cummings, M.L., Display Design in the F/A-18 Hornet, Ergonomics in Design (2003) Vol. 11(4).
- [5] Billings, C.E. (1997). Aviation Automation: The Search For A Human-Centered Approach. Hillsdale, N.J: Lawrence Erlbaum Associates.
- [6] Endsley, M. and Kiris, E. (1995). The out-of-the-loop performance problem and level of control in automation. Human Factors, 37(2), 381-394.
- [7] Hancock, P.A. and Scallen, S.F. (1998). Allocating functions in human-machine systems. In: R. Hoffman and M. Sherrick and J. Warm (Eds.), Viewing psychology as a whole: The integrative science of William N. Dember (pp. 509-539). Washington DC: American Psychological Association.
- [8] Moray, N., Inagaki, T. and Itoh, M. (2000). Adaptive Automation, Trust, and Self-Confidence in Fault Management of Time-Critical Tasks. Journal of Experimental Psychology: Applied, 6(1), 44-58.
- [9] Sarter, N.B. and Schroeder, B., Supporting decision making and action selection under time pressure and uncertainty: The case of in-flight icing, Human Factors, 43, 2001, 573-583.
- [10] Scerbo, M.W. (1996). Theoretical perspectives on adaptive automation. In: R. Parasuraman and M. Mouloua (Eds.), Automation and human performance: Theory and applications. Mahwah, NJ: Erlbaum.

4.3 MIGRATION OF OPERATOR CONTROL: HUMAN FACTORS AND TEAMING ISSUES

4.3.1 Background

As noted by Gawron [1] specifically with regards to uninhabited aerial vehicles (UAVs), the advent of uninhabited military vehicles (UMVs) has created a host of new human factors challenges which arise primarily because the vehicle and the operator are no longer necessarily co-located [2]. Perhaps one of the most unique of these UMV specific human factors challenges concerns migration of operator control. While migration implies movement, the construct of control migration used in this work will be similar to that described by Kahne [3] and includes changes in the locus of control within functional, temporal, or physical domains. For instance, in current long endurance UAV operations, control may be transferred between operators in a control station (e.g., crew changeover), between control stations (e.g., vehicle handoff), or among members of a crew (e.g., task execution) [4]. Although migration of operator control has been a factor in several UAV mishaps [5,6], there are currently no relevant studies in the literature addressing this issue in either UAVs [4] or other UMV systems. For autonomous UMVs requiring only supervisory control, studies of air traffic control (ATC) can serve as an analog supervisory control domain [7]. However, while ATC issues instructions to aircraft, ATC's role is ultimately advisory rather than mandatory since legal responsibility for the safety of the aircraft and its occupants rests with the pilot [8]. Thus, this section will necessarily be more of a theoretical discussion of migration of operator control rather than a review of empirical evidence. In particular, migration of operator control in UMVs will be explored as a novel application of the fields of team processes and team communications. First, the current state of knowledge regarding migration of operator control in the most mature UMV technology (e.g., UAVs) will be reviewed with the understanding there are logical applications to future ground or maritime UMVs as well. This will be followed by discussions of the potential reasons for and the advantages and disadvantages of migrating operator control, the impact of migrating operator control on team dynamics, important issues which need to be resolved, and potential strategies to address or mitigate those issues.

4.3.1.1 References

- [1] Gawron, V.J. (1998). Human factors issues in the development, evaluation, and operation of uninhabited aerial vehicles. AUVSI '98: Proceedings of the Association of Uninhabited Vehicle Systems International, 431-438.
- [2] McCarley, J.S. and Wickens, C.D. (2004). Human factors concerns in UAV flight. Retrieved July 30, 2005, from <http://www.hf.faa.gov/docs/508/docs/uavFY04Planrpt.pdf>
- [3] Kahne, S. (1983). Control migration: A characteristic of C3 systems. Control Systems Magazine, 15-19.
- [4] McCarley, J.S. and Wickens, C.D. (2005). Human factors implications of UAVs in the national airspace. Retrieved July 30, 2005, from <http://www.humanfactors.uiuc.edu/>
- [5] Tvaryanas, A.P. (2004, May). USAF UAV mishap epidemiology, 1997-2003. Distributed at the Human Factors in Uninhabited Aerial Vehicles First Annual Workshop, Mesa, AZ.
- [6] Woods, D. (1988). Coping with the complexity: the psychology of human behaviour in complex systems. In: Tasks, Errors & Mental Models, Goodstein J., Andersen H., Olsen B. (Eds), Taylor & Francis, London, 128-148.

- [7] Cummings, M.L. and Guerlain, S. (2004). Human performance issues in supervisory control of autonomous airborne vehicles. Retrieved August 9, 2005, from http://web.mit.edu/aeroastro/www/people/missyc/pdfs/AUVSI_Cummings.pdf
- [8] Hopkins, V.D. (1970). Human factors in the ground control of aircraft (AGARD-AG-142). Neuilly-sur-Seine, France: North Atlantic Treaty Organisation.

4.3.2 Migration of UAV Operator Control

4.3.2.1 Levels of Control

Standardization Agreement (STANAG) 4586, Standard Interfaces of the UAV Control System for North Atlantic Treaty Organisation (NATO) Interoperability, defines five different Levels of Interoperability (LOIs) or degrees of control for UAVs (A. Kirschbaum, personal communication, August 17, 2005):

Level 1: Reception and transmission of secondary imagery or data.

Level 2: Reception of imagery or data directly from the UAV.

Level 3: Control of the UAV payload.

Level 4: Control of the UAV, without takeoff and landing.

Level 5: Full function and control of the UAV to include takeoff and landing.

Control complexity increases from level 1 to level 5 with each subsequent level including the capabilities of the former level(s) (Figure 4-3). Implicit in this control taxonomy is the understanding that a variety of transfers between LOIs may be necessary during a single UAV mission. STANAG 4586 describes these LOIs without reference to a specific UAV category. Nor does the standard clearly state if these LOIs apply only to the dedicated UAV control station or if they also apply to downstream users of the information derived directly from the UAV. Certainly allowing a user more control of the system has the potential to enhance mission execution by decreasing the number of intermediary personnel. However, the higher the LOI, the more costly the equipment and the more specialized the training required [1].

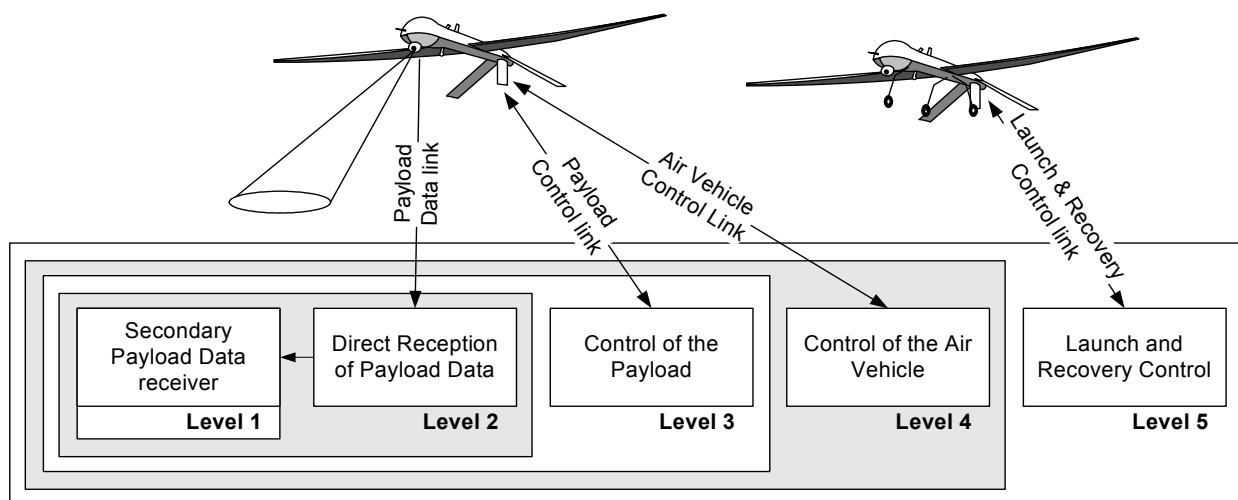


Figure 4-3: Levels of UAV Interoperability and the Respective Communication Links.

4.3.2.2 Types of Control Migration

4.3.2.2.1 Changeover

A changeover is the migration of vehicle or payload control from one (group of) operator(s) to another (group of) operator(s) at the same location. It is possible during a changeover to have a face-to-face debrief. Also, since the same equipment is used, there is no need for system changes or data transmission link reconnections. Additionally, a changeover will generally not require coordination with ATC or other external command and control (C2) agencies. Types of changeovers include:

- **Time transfer:** Time transfer implies the operators are identical in skill and function and control is transferred because the endurance of the vehicle exceeds that of the operator(s). Very long UAV missions may require several time transfers.
- **Function transfer:** Function transfer implies the operators must accomplish different tasks during the same mission, possibly in another system-mode or even at a different part of the system. For example, an operator may merely perform navigation and safety monitoring tasks in coordination with ATC during the ferry to the theatre of operations (TOO), but once in the TOO, may change to a more payload driven way of operations (Figure 4-4). This form of transfer can be combined with a changeover.
- **Skill transfer:** Skill transfer implies the operators are trained differently and the transfer is required as the vehicle performs different tasks. This kind of transfer may be performed when less experienced operators operate the vehicle or payload for simple tasks while more skilled operators take over for complex tasks.

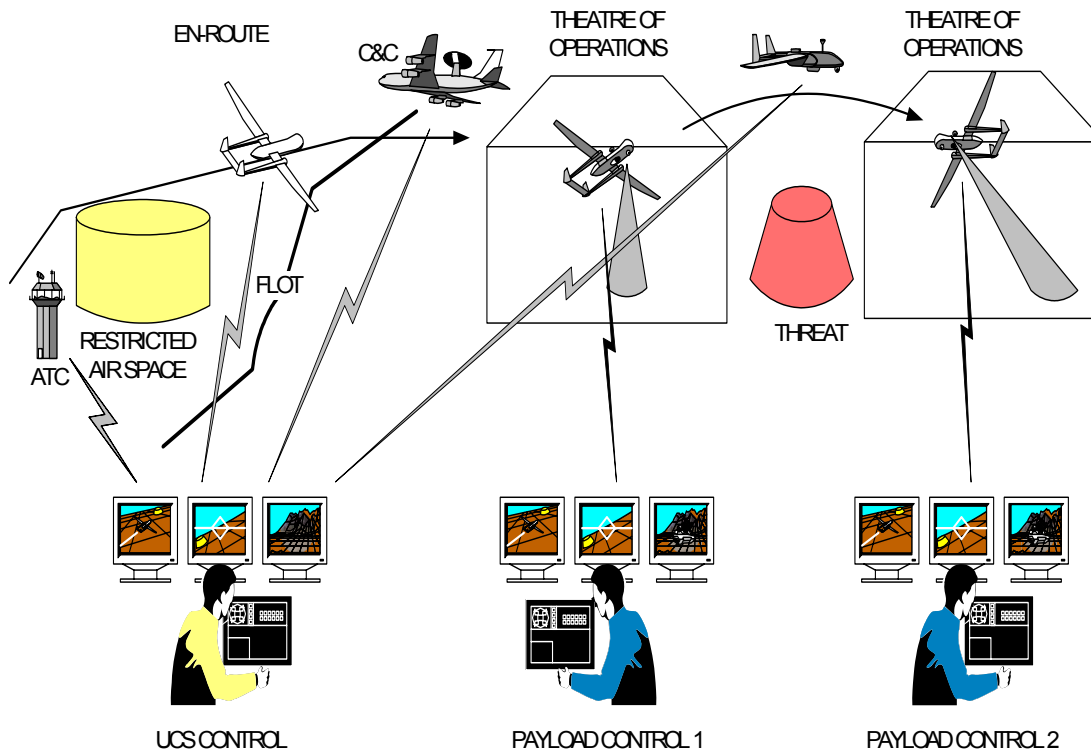


Figure 4-4: Functional Transfer and Time Transfer of the UAV during Different Mission Phases.

A handoff or handover involves the migration of vehicle or payload control from one location to another location. Often the term handover is used when the transfer is performed between two similar control systems (e.g., two identical control stations). In contrast, the term handoff is used when the transfer is performed between two dissimilar control systems (e.g., changes between LOIs).

4.3.2.2.2 *Vehicle versus Payload*

Both a changeover and a handoff may be used to transfer control of both the vehicle and payload or solely the payload. A vehicle transfer implies operators transfer control of the vehicle to include the following: a) vehicle command and control, b) navigation, c) voice communications, d) vehicle safety and emergency responsibility, e) payload control, and f) data transmission link control and monitoring. In contrast, a payload-only transfer implies operators retain control of the vehicle (items a-d) and only transfer control of the payload. Payload-only transfer appears less complex than vehicle transfer because overall responsibility for the vehicle does not change. However, if a large area must be covered or objects of interest are mobile, a high degree of coordination is required between the vehicle and payload operators in order to keep the UMV path within sensor constraints. This may significantly increase the workload of both operators and have a negative effect on the operators' situational awareness (SA).

4.3.2.3 References

- [1] Theunissen, E., Goossens, A.A.H.E., Bleeker, O.F. and Koeners, G.J.M. (2004, August). UAV mission management functions to support integration in a strategic and tactical ATC and C2 environment (AIAA 2005-6310). Presented at the AIAA Modeling and Simulation Technologies Conference and Exhibit, San Francisco, California.

4.3.3 Reasons for Migrating Operator Control

4.3.3.1 Limitations Necessitating Control Migration

4.3.3.1.1 *Temporal Limits*

Many current human-machine operations are continuous in character and the nature of these operations often precludes a temporary shutdown because of economical or other constraints [1]. Such operations also have the potential to create situations in which people are driven to work continuously. This has certainly been the case in military operations where technological advances in night vision devices and other sensors coupled with a global battle space has led to a doctrine of continuous, around-the-clock operations [2,3]. Thus, current military endurance UAV systems operate at distances requiring beyond-line-of-sight communications and can remain airborne for nearly 1 – 2 days. Future military and civil UMV systems are projected to operate for durations of days to months at a time [4,5,6].

A critical problem for such endurance UMV systems is the predictable decrements experienced by individuals continuously performing cognitive tasks for sustained periods [1,3]. In a study comparing the effects of fatigue versus alcohol intoxication, Dawson and Reid [7] found the hourly performance decrement for each hour of wakefulness between 10 and 26 hours was equivalent to the performance decrement observed with a 0.004 percent rise in blood alcohol concentration. Therefore, after 17 hours of sustained wakefulness, cognitive psychomotor performance decreases to a level equivalent to the performance impairment observed at a blood alcohol concentration of 0.05 percent. This is the proscribed level for alcohol intoxication in many western industrialized countries [2,7] and exceeds the 0.04 percent limit established by the Federal Aviation Administration for aircrew [8]. Mullaney, et al. [9,10,11] conducted studies of continuous performance on

monotonous tasks requiring sustained attention and found such performance produced rapid fatigue effects after only 6 hours. More than half of the study participants experienced psychological disturbances such as mild hallucinations, illusions, disorientation, and derealizations, mostly after 18 hours. Finally, the operational impact of fatigue-related performance decrements was demonstrated by an Air Force Safety Center study which found fatigue was present in 12.7 percent of the most serious class of Air Force mishaps occurring during fiscal years 1972 – 2000 [12], costing the Air Force an estimated 54 million dollars each year [2].

While it is obviously unreasonable to expect a single operator to control a UMV with an endurance greater than 1 day, it is also evident operators will need to be changed during UMV operations spanning more than the majority of a day. Summarizing NASA's experience testing UAVs, Del Frante and Cosentino [13] stressed the importance of adhering to established crew rest requirements, implying UMV operations are not immune to fatigue-related operator performance decrements. Additionally, studies of personnel working 8, 10, and 12 hour shifts [14,15,16,17,18] have shown increased fatigue and poorer performance with 12-hour versus eight or ten hour shifts. Collectively, these studies suggest migration of operator control is a necessity as UMV endurances routinely exceed 12 hours, although optimally it should be considered after 8 – 10 hours.

4.3.3.1.2 Physical Limits

As previously mentioned, some military endurance UAVs currently operate at great distances from the control station, necessitating beyond-line-of-sight communications [5,6]. As satellites or other UMVs are used to relay signals over the horizon, variable time delays or latencies of one or more seconds are introduced. However, latencies greater than one second mean real-time feedback necessary for effective manual control is not available [19]. Additionally, many UMV operators are dependent on real-time imagery from cameras mounted on the remote vehicle in order to manually control the vehicle [20]. This requires data transmission links between the vehicle and control station with high bandwidths and low latencies, but increasing distance between the vehicle and control station, especially beyond line-of-sight, necessarily forces constraints on data link bandwidth and latency [20,21,22]. Such data link constraints can result in limited temporal resolution, spatial resolution, color, and field of view of imagery irrespective of onboard sensor capabilities [20,23]. With great enough distances, the frequency and immediacy of transmitted images may decrease to the point where direct manual control of the vehicle is significantly degraded [21,24]. Besides vehicle control, experimental evidence has also shown visual tasks such as target detection and identification, tracking, and orientation are affected by degraded image quality, slow update rates (< 2 Hz) and high latency (> 2 sec) [20,25].

Increased automation (e.g., supervisory control) and predictive displays have been utilized to mitigate the effects of control latency [24,19]. However, there are situations where manual control modes may be preferred over supervisory control or a fully automated vehicle [20]. In such situations, an alternative strategy may be to handoff control to more proximate control stations. This approach has relative merit over supervisory control in situations where concerns over control latency and quality of visual imagery or sensor information are critical, such as in highly dynamic and changing environments where near-real time data is required for complex decision-making [21,20]. These situations might include weapons employment [24] when there is a risk for fratricide or responding to a malfunctioning or damaged remote vehicle. Additionally, some current military UAVs by design must be manually controlled during takeoff and landing [21,6,20]. In these circumstances, a control station needs to be located in line-of-sight distance of the airfield to minimize data transmission delays and optimize manual control. However, once airborne, control is handed off to a geographically remote control station where the UAV is operated via supervisory control, thereby minimizing the equipment and personnel which must be sent to a potentially vulnerable forward base of operations.

4.3.3.1.3 *Functional Limits*

Migration of control within a crew may occur when a UMV system is designed such that control is functionally divided between non-equivalent controllers. For instance, current military UAVs are typically operated by at least two operators with one responsible for vehicle control and the other for payload control [21,20]. While the payload operator usually does not directly control the vehicle, it may be possible for this individual to exercise indirect control of a UMV if it is designed to autonomously adjust its path to stabilize camera or sensor images. Functional migration of control also occurs in some military tactical UAVs (TUAVs) where responsibility for takeoff/landing and en route control is divided between two operators. In this situation, the external pilot (EP) interacts with the TUAV while in direct visual contact at the site of takeoff or landing. In contrast, the air vehicle operator (AVO) is inside a control station and interacts with the TUAV through an interface of sensor displays and controls during the en route phase of flight [26,6,27]. While control is functionally divided in part out of necessity because of task-specific human-machine interfaces (HMIs), Barnes et al. [26] also demonstrated differences between EPs and AVOs with regards to operator abilities across multiple cognitive skill sets.

4.3.3.2 **Advantages of Control Migration**

4.3.3.2.1 *Mitigate Fatigue and Optimize Operator Vigilance*

In highly automated systems such as UMVs, much of the operator's task load is supervisory in nature, consisting mainly of passive monitoring of system parameters and remaining alert for malfunctions [28,20]. This trend towards placing the operator in the role of passive monitor has continued despite years of vigilance research demonstrating such roles make maintaining a constant level of alertness exceedingly difficult [29,30,31,32] and predispose to "hazardous states of awareness" [33]. Studies of vigilance tasks have consistently demonstrated a vigilance decrement beginning as early as 20 – 35 minutes after initiation of a task and characterized by declining numbers of correct responses and/or increasing response times [29,3,19]. One study found declining detection rates after only 2 – 3 minutes of task performance, with target detection rates eventually plateauing at 70 – 80 percent of initial rates [34]. Prolonged vigilance work generally invokes subjective feelings of boredom and monotony and invariably induces decreased levels of physiologic arousal. Boredom in particular can become apparent within minutes of the onset of a monotonous task and is associated with decreased performance efficiency and increased drowsiness. However, when coupled with the need to maintain high levels of alertness, vigilance tasks can be perceived as quite stressful [3,35]. This stress predisposes the operator to short term fatigue which typically manifests as long response times, missed signals, and brief interruptions in performance due to gaps or lapses in attention [36] as well as increased decision errors or decreased throughput (e.g., maintain accuracy at the expense of performance speed) [3]. Thus, it should be expected that tasks requiring the sustained attention of UMV operators will be susceptible to degraded performance and increased risk for operational errors [28].

Although initial research [1,37] with complex monitoring tasks typical of the ATC task environment suggested vigilance decrements did not occur, more recent studies are supportive of the vigilance decrement in both simple and complex monitoring tasks [29,39,36,40]. The validity of these concerns in UMV operations was demonstrated in a study of Army UAV operator performance under two experimental conditions involving 8 – 10 hour versus 3 hour flights [41]. Target detection and recognition performance as well as crew reaction times were significantly degraded during nocturnal operations involving the longer flights while no nocturnal changes were observed for the shorter flights. Likewise, two studies [36,40] using an ATC task found the time to detect and the frequency of missed traffic conflicts increased significantly over the course of just 2 hours. These vigilant decrements were attributed to increasing lapses in attention rather than a generalized fatigue effect.

One of the best ways to overcome these effects is change, whether using work breaks, rest pauses, or split shifts, although the benefits of rest pauses may derive more from subjective factors such as relief of boredom [3]. Warm [42] in particular recommended continuous vigilance monitoring tasks be kept to less than 4 hours in duration. Regardless of the method of change, it will necessarily involve the migration of control to another operator, whether in the same or another control station. Thus, migration of operator control plays a potentially critical role in the maintenance of optimum operator performance and decreasing risk for operational errors.

4.3.3.2.2 *Operator Functional Specialization*

Unlike manned vehicles where crew size is limited by vehicle payload constraints and all operator functional capabilities must be resident in the onboard crew, UMVs offer a distinct advantage of allowing these functional capabilities to be distributed over a multitude of potentially geographically dispersed specialists. In essence, a UMV crew is limited only by data transmission link accessibility. Given the massive amounts of information currently down-linked from UMV systems [28] and the information processing constraints necessarily imposed by the sequential decision-making of human operators [43], it is key to distribute this information so it can be more efficiently processed for mission accomplishment [28]. This point was highlighted by a study of human systems integration (HSI) issues in military UAV mishaps which found an association between failures in the cognitive domain and operational errors [44].

Beyond the issue of information processing, UMVs offer the opportunity to employ task specialization beyond the level hereto seen in traditional manned vehicles. The potential need for task specialization in UMV operations can be understood given the current military experience with UAVs in which training and attentional issues are frequent causal factors in human error-related mishaps [45]. As noted by Barnes et al. [26] in their study of Army UAV operators, experience improves operators' cognitive throughput, allowing them to devote limited attentional resources to future problems while automatically attending to immediate perceptual and motor tasks. This was echoed in NASA's lessons learned testing UAVs [13] that "even more important than practicing the emergency procedures is practicing the normal procedures to the point that they are second nature" so anomalies are addressed with increased attention. Thus, experience serves to increase an operator's cognitive efficiency in problem solving by effectively increasing attentional resources [19]. Unfortunately, the cognitive efficiency obtained via experience is specific to the tasks experienced and not broadly generalizable [26].

Given the task-centric nature of expertise, consideration should be given to the creation of specialty teams to intervene and handle uncommon or off-nominal events. Such teams could rehearse infrequent tasks and explore potential outcomes, thereby developing proficiency in situational problem solving prior to encountering the actual event. For example, rather than training all operators to handle emergencies, specialty teams could be trained to take control of the vehicle and troubleshoot a malfunctioning or damaged UMV. These emergency teams could operate from remote control stations equipped with enhanced displays to aid diagnosis and allow predictive simulation. Such methods have been used successfully in the U.S. space program [28].

Functional specialization may also be utilized in non-emergent, nominal situations to optimize the central role of the human decision-maker within the system. In traditional manned combat vehicles, the local operator has the responsibility to authenticate targets and trigger weapons because they are presumed to be in the best position to assess the situation and make timely decisions. However, UMVs allow this function to be migrated to other team members possessing higher levels of technical or combat expertise such as a target detection specialist or experienced mission commander, thereby improving the confidence level of information

presented to controlling authorities [28]. Additionally, functional specialization allows for increased training program efficiency since all personnel don't need to receive equal training. The FAA has explored this issue with regards to training air traffic control specialists [46] and the Air Force has adopted this approach in training MQ-1 Predator operators on takeoff and landing.

4.3.3.2.3 *Workload and Multiple Vehicle Control*

There currently is a limited body of human factors research suggesting one operator may control more than one UMV under relatively idealized conditions to include closely coordinated and correlated vehicle activities, a stable environment, and reliable automation [38,47,48,6]. However, research has also demonstrated that operator performance controlling a single vehicle is significantly degraded when heavy demands are imposed by payload operations [41,49,25]. This would suggest the ability of an operator to attend to multiple UMVs may be severely compromised under non-idealized conditions, especially if one vehicle is malfunctioning or damaged [6]. Additional human factors research is available examining situational awareness in ATC, an analog for supervisory control of multiple vehicles. Endsley and Rodgers [50] found air traffic controller accuracy was significantly impacted by the number of aircraft being controlled and situational awareness declined dramatically when the number of aircraft exceeded 8 – 10. This is consistent with the magic number “ 7 ± 2 ” in memory research [51] which states there are finite limits on human information processing beyond which people tend to forget. Two studies [52,22] examining air traffic controller performance when passively monitoring aircraft under free flight conditions found a significant decrement in situational awareness when controllers had to handle 17 versus 11 aircraft. Additionally, a study examining control of multiple retargetable missiles [38] found operators could effectively control 8 – 12 missiles, but performance degraded with 16 missiles. The preponderance of the evidence thus suggests greater than 12 vehicles potentially represents a cognitive saturation state for controllers interacting with semi-autonomous vehicles requiring only the setting of new goals [53].

Given the suggested limits to an operator's ability to manage multiple UMVs, migration of control may be utilized as a workload mitigation strategy. For example, an operator controlling multiple UMVs under high workload conditions (e.g., multiple vehicle requests for operator attention) could transfer control of one or more UMVs to other operators under low workload conditions, even as part of normal operations. In cases where a single UMV requires sustained attention because of a backlog of vehicle requests for operator attention or off-nominal operating conditions, control of this high workload UMV could be transferred to an on-call operator or supervisor akin to current ATC practices. The ability to transfer control of UMVs based on workload prevents a single operator controlling multiple UMVs from having to adopt triage-like procedures for handling multiple attentional demands [28].

4.3.3.2.4 *Payload Control*

As already alluded to during the discussion of multiple vehicle control, performing payload tasks can significantly increase operator workload and degrade operator performance. In current military reconnaissance UAVs, vehicle and payload control are typically divided between a vehicle operator and a payload operator [21,25]. Van Erp and Van Breda [25] concluded such a crew structure was reasonable in light of findings that consolidating vehicle and payload control within a single operator substantially degraded performance. Likewise, Barnes and Matz [41] studied a UAV control station configuration which required a single operator to perform both aviation and target acquisition functions. They found operators became focused on the targeting function to the detriment of situational awareness and vehicle control, leading the authors to question the wisdom of using a single operator. Two additional studies demonstrated attentional fixation and cognitive tunneling during target analysis which degraded performance on other tasks irrespective of level of automation or use of auditory cueing [47,49]. The task of manipulating a camera image, analyzing targets,

and keeping track of cardinal directions appears to be sufficiently challenging that timesharing with other tasks such as vehicle control becomes virtually impossible. Finally, Van Breda and Passenier [54] noted operator performance was poor when utilizing “double-stick” controls where one joystick controls airframe heading and speed and the other camera heading and pitch. However, this is not surprising given such control arrangements predispose to perceptual confusion which increases the potential for action slip errors [19].

Nevertheless, for optimal flexibility and cost effectiveness, it is desirable to allocate both vehicle and payload control to one operator [54]. It may therefore be necessary to delineate circumstances under which vehicle and payload control may be safely performed by a single UMV operator and when control of the payload should be transferred to another operator [6]. This may be decided prior to a mission or payload control may need to be transferred during a mission in response to a dynamically evolving situation. As previously discussed, a UMV operator’s ability to perform payload-oriented visual tasks such as target detection and identification, tracking, and orientation is impaired by low temporal update rates and long transmission delays [20,25]. If vehicle control is adequate for the task using some form of supervisory control, it may only be necessary to handoff payload control to a more proximate control station, potentially eliminating the need for full control stations in forward locations. Additionally, the ability to handoff payload control to those directly requesting the camera imagery or sensor data (e.g., target detection specialists or fielded forces) could increase the efficiency of data collection and eliminate the need for coordination with an intermediate payload operator. At the extreme, control of weapons could be transferred to the forces requesting their employment, hopefully decreasing the risk for fratricide.

4.3.3.3 Disadvantages of Migrating Operator Control

4.3.3.3.1 Situational Awareness

While there are good reasons to consider utilizing migration of operator control in UMVs, it is important to also explore the potential pitfalls. Indeed, migration of control may well constitute a critical and potentially high workload phase for UMV operators [6]. For example, several military UAV accidents have occurred either directly during or indirectly as the result of changeovers or handoffs [6,55,27]. In handing off control between stations, mishaps have resulted when the station receiving control was improperly configured [27]. During changeovers, mishaps have resulted because of the new operator’s decreased systems awareness [55]. More broadly, there is also concern for an acute decrement in crew situational awareness when control is transferred to a crew not currently involved in the ongoing mission [55]. Kidd and Kinkade [1] demonstrated the existence of such an operator change-over performance decrement in the ATC environment. Controller performance was markedly decreased over the first 5 minute period following assumption of controller duties. This change-over performance decrement was mitigated by about 50 percent if either parallel control or auditory-plus-visual monitoring was employed as a pretransition condition. Another study examining operational errors in ATC [56] found errors were most frequent during the first 15 minutes after assuming controller duties and nearly half occurred within the first 30 minutes on position. Likewise, a study of Army UAV operators [41] found operators preferred longer over shorter rotations because they perceived the longer rotations allowed for better situational awareness of the tactical environment.

4.3.3.3.2 Complex Teaming Situations

Migrating operator control can create distributed crews with dynamically changing membership which may have significant associated costs in terms of the increased complexity of crew coordination and communication [57,6]. Breakdowns in team performance, cooperation, and communication have been shown to be a contributing factor in military UAV mishaps [45]. Complex teaming situations dictate the need for highly efficient, structured, and reliable communication. Unfortunately, the nature of human-human and

human-machine teams in high stress environments tends to create an unfavorable climate for successful communication. With respect to human behavior, emotion, information overload, and a lack of situational awareness comprise a few of the factors which impede the production and processing of messages, resulting in low fidelity communication.

Supporting complex teaming situations is further complicated by the densely bureaucratic nature of military and governmental bodies. The culture and structure of these types of organizations has historically been characterized by rigid, formal, and delayed communication. Large, structured networks constrain communication, which results in delayed information processing and a lagging response to environmental stimuli. A change in organizational structure from a traditional management hierarchy to a self-organizing system of self-managed, mixed-entity teams can improve the military's ability to respond to critical C2 situations.

4.3.3.4 References

- [1] Kidd, J.S. and Kinkade, R.G. (1959). Operator change-over effects in a complex task (WADC TR 59-235). Wright-Patterson AFB, OH: USAF Wright Air Development Center.
- [2] Caldwell, J.A. (2003). Fatigue in aviation operations. Retrieved August 9, 2005, from <http://www.afrlhorizons.com/Briefs/Jun03/HE0301.html>
- [3] Krueger, G.P. (1991). Sustained military performance in continuous operations: Combatant fatigue, rest and sleep needs. In: R. Gal and A.D. Mangelsdorff, A.D. (Eds.), Handbook of Military Psychology (pp. 255-277). New York: Wiley.
- [4] Curry, M. (2005). NASA – Past projects – Helios prototype. Retrieved July 30, 2005, from <http://www.nasa.gov/centers/Dryden/history/pastprojects/Erast/helios.html>
- [5] Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (2002). Uninhabited aerial vehicle roadmap 2002-2027. Retrieved July 30, 2005 from http://www.acq.osd.mil/usd/uav_roadmap.pdf
- [6] McCarley, J.S. and Wickens, C.D. (2005). Human factors implications of UAVs in the national airspace. Retrieved July 30, 2005, from <http://www.humanfactors.uiuc.edu/>
- [7] Dawson, D. and Reid, K. (1997). Fatigue, alcohol and performance impairment. *Nature*, 338, 235.
- [8] Ferrell, W.R. and Sheridan, T.B. (1966). Supervisory control remote manipulation. IEEE Nerem record, Northeast electronic research and engineering meeting November 2, 16-17. Boston.
- [9] Mullaney, D.J., Fleck, P.A., Okudaira, N. and Kripke, D.F. (1985). An automated system for administering continuous workload and for measuring sustained continuous performance. *Behavior Research Methods, Instruments, and Computers*, 17, 16-18.
- [10] Mullaney, D.J., Kripke, P.A., Fleck, P.A. and Johnson, L.C. (1983a). Sleep loss and nap effects on sustained continuous performance. *Psychophysiology*, 20, 643-651.
- [11] Mullaney, D.J., Kripke, D.F., Fleck, P.A. and Okudaira, N. (1983b). Effects of sustained continuous performance on subjects working alone and in pairs. *Perceptual and Motor Skills*, 57, 819-832.

- [12] Air Force Safety Center (2002). Fatigue data summary of class A mishaps from 1972-2000. Kirtland AFB, NM: Air Force Safety Center.
- [13] Del Frate, J.H. and Cosentino, G.B. (1998). Recent flight test experience with uninhabited aerial vehicles at the NASA Dryden Flight Research Center (NASA/TM-1998-206546). Edwards AFB, CA: Dryden Flight Research Center.
- [14] Rosa, R.R. (1991). Performance, alertness and sleep after 3-5 years of 12 h shifts: A follow-up study. *Work and Stress*, 5, 107-116.
- [15] Rosa, R.R. and Bonnet, M.H. (1993). Performance and alertness on 8 h and 12 h rotating shifts at a natural gas utility. *Ergonomics* 36, 1177-1193.
- [16] Rosa, R.R., Colligan, M.J. and Lewis P. (1989). Extended workdays: Effects of 8-hour and 12-hour rotating shift schedules on performance, subjective alertness, sleep patterns, and psycho-social variables. *Work and Stress*, 3, 21-32.
- [17] Rosa, R.R., Wheeler, D.D., Warm, J.S. and Colligan, M.J. (1985). Extended workdays: Effects on performance and ratings of fatigue and alertness. *Behavior Research Methods, Instruments, and Computers*, 17, 6-15.
- [18] Schroder, D.J., Rosa, R.R. and Witt, L.A. (1995). Some effects of 8- vs. 10-hour work schedules on the test performance/alertness of air traffic control specialists (DOT/FAA/AM-95/32). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [19] Wickens, C.D. and Hollands, J.G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River: Prentice Hall.
- [20] Van Erp, J.B.F. (2000). Controlling uninhabited vehicles: The human factors solution. RTO Meeting Proceedings 44 (RTO-MP-44), B8.1-B8.12.
- [21] McCarley, J.S. and Wickens, C.D. (2004). Human factors concerns in UAV flight. Retrieved July 30, 2005, from <http://www.hf.faa.gov/docs/508/docs/uavFY04Planrpt.pdf>
- [22] Metzger, U. and Parasuraman, R. (2001). The role of the air traffic controller in future air traffic management: An empirical study of active control versus passive monitoring. *Human Factors*, 43, 519-528.
- [23] Van Erp, J.B.F. and Kappé, B. (1996). Computer generated environment for steering a simulated uninhabited aerial vehicle (TNO-report TM-96-A039). Soesterberg, The Netherlands: TNO Human Factors Research Institute.
- [24] Mouloua, M., Gilson, R., Daskarolis-Kring, E., Kring, J. and Hancock P. (2001a). Ergonomics of UAV/UCAV mission success: Consideration for data link, control, and display issues. *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting*, 144-148.
- [25] Van Erp, J.B.F. and Van Breda, L. (1999). Human factors issues and advanced interface design in maritime uninhabited aerial vehicles: A project overview (TNO-report TM-99-A004). Soesterberg, The Netherlands: TNO Human Factors Research Institute.

- [26] Barnes, M.J., Knapp, B.G., Tillman, B.W., Walters, B.A. and Velicki, D. (2000). Crew systems analysis of uninhabited aerial vehicle (UAV) future job and tasking environments (ARL-TR-2081). Aberdeen Proving Ground, MD: Army Research Laboratory.
- [27] Woods, D. (1988). Coping with the complexity: the psychology of human behaviour in complex systems. In: Tasks, Errors & Mental Models, Goodstein J., Andersen H., Olsen B. (Eds), Taylor & Francis, London, 128-148.
- [28] Mouloua, M., Gilson, R., Kring, J. and Hancock, P. (2001b). Workload, situation awareness, and teaming issues for UAV/UCAV operations. Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting, 162-165.
- [29] Davies, D.R. and Parasuraman, R. (1982). The psychology of vigilance. London: Academic Press.
- [30] Makeig, S., Elliott, F.S. and Postal, M. (1993). First demonstration of an alertness monitoring management system (Report No. 93-36). Bethesda, MD: Naval Health Research Center.
- [31] Parasuraman, R. (1987). Human-computer monitoring. Human Factors, 29, 695-706.
- [32] Woods, D. (1988). Coping with the complexity: the psychology of human behaviour in complex systems. In: Tasks, Errors & Mental Models, Goodstein J., Andersen H., Olsen B. (Eds), Taylor & Francis, London, 128-148.
- [33] Pope, A.T. and Bogart, E.H. (1992). Identification of hazardous awareness states in monitoring environments. SAE 1992 Transactions: Journal of Aerospace, 101, 448-457.
- [34] Makeig, S., Elliott, F.S., Inlow, M. and Kobus, D.A. (1990). Predicting lapses in vigilance using brain evoked responses to irrelevant auditory probes (TR 90-39). San Diego, CA: Naval Health Research Center.
- [35] Thackray, R.I. (1980). Boredom and monotony as a consequence of automation: A consideration of the evidence relating boredom and monotony to stress (DOT/FAA/AM-80/1). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [36] Schroder, D.J., Touchstone, R.M., Stern, J.A., Stoliarov, N. and Thackray, R. (1994). Maintaining vigilance on a simulated ATC monitoring task across repeated sessions (DOT/FAA/AM-94/6). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [37] Shaw, W.J. (1955). The effects of continued performance in a task of air traffic control. Perceptual and Motor Skills, 5, 167.
- [38] Cummings, M.L. and Guerlain, S. (2004). Human performance issues in supervisory control of autonomous airborne vehicles. Retrieved August 9, 2005, from http://web.mit.edu/aeroastro/www/people/missyc/pdfs/AUVSI_Cummings.pdf
- [39] Molloy, R. and Parasuraman, R. (1996). Monitoring an automated system for a single failure: Vigilance and task complexity effects. Human Factors, 38, 311-322.

- [40] Thackray, R.I. and Touchstone, R.M. (1988). An evaluation of the effects of high visual taskload on the separate behaviors involved in complex monitoring performance (DOT/FAA/AM-88/1). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [41] Barnes, M.J. and Matz, M.F. (1998). Crew simulations for uninhabited aerial vehicle (UAV) applications: Sustained effects, shift factors, interface issues, and crew size. Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting, 143-147.
- [42] Warm, J.S. (Ed.) (1984). Sustained attention in human performance. New York: John Wiley & Sons.
- [43] Kahne, S. (1983). Control migration: A characteristic of C3 systems. Control Systems Magazine, 15-19.
- [44] Tvaryanas, A.P., Thompson, W.T. and Constable, S.H. (2005a). The U.S. military uninhabited aerial vehicle (UAV) experience: Evidence-based human systems integration (HSI) lessons learned. Proceedings of the NATO/RTO Human Factors and Medicine Panel (HFM) Symposium on Strategies to Maintain Combat Readiness During Extended Deployments – A Human Systems Approach (RTO-MP-HFM-124/P5). Neuilly-sur-Seine, France: North Atlantic Treaty Organisation/Research and Technology Organisation.
- [45] Tvaryanas, A.P., Thompson, W.T. and Constable, S.H. (2005b). U.S. military uninhabited aerial vehicle mishaps: Assessment of the role of human factors using the human factors analysis and classification system (HFACS) (HSW-PE-BR-TR-2005-0001). Brooks City-Base, TX: USAF 311th Performance Enhancement Directorate.
- [46] Thompson, R.C., Agen, R.A. and Broach, D.M. (1998). Differential training needs and abilities at air traffic control towers: Should all controllers be trained equally? (DOT/FAA/AM-98/8). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [47] Dixon, S.R. and Wickens, C.D. (2003a). Control of multiple-UAVs: A workload analysis. Retrieved August 9, 2005, from <http://www.humanfactors.uiuc.edu/Reports&PapersPDFs/isap03/dixwic.pdf>
- [48] Dixon, S.R. and Wickens, C.D. (2003b). Imperfect automation in uninhabited aerial vehicle flight control. Retrieved August 9, 2005, from <http://www.humanfactors.uiuc.edu/Reports&PapersPDFs/TechReport/03-17.pdf>
- [49] Walker, C. and Dooley, K.J. (1999). The stability of self-organized rule-following work teams. Computational & Mathematical Organization Theory, 5(1), 5-30.
- [50] Endsley, M.R. and Rodgers, M.D. (1997). Distribution of attention, situational awareness, and workload in a passive air traffic control task: Implications for operational errors and automation (DOT/FAA/AM-97/13). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [51] Miller, G.A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63, 81-87.
- [52] Galster, S.M., Duley, J.A., Masalonis, A.J. and Parasuraman, R. (2001). Air traffic controller performance and workload under mature free flight: Conflict detection and resolution of aircraft self-separation. International Journal of Aviation Psychology, 11, 71-93.

- [53] Cummings, M.L. and Mitchell, P.J. (2005). Management of multiple dynamic human supervisory control tasks for UAVs. Retrieved August 9, 2005, from http://web.mit.edu/aeroastro/www/labs/halab/papers/HCI2005_cummings2.pdf
- [54] Van Breda, L. and Passenier, P.O. (1993). An exploratory study of the human-machine interface for controlling a maritime uninhabited air vehicle (Report IZF 1993 A-10). Soesterberg, The Netherlands: TNO Institute for Perception.
- [55] Tvaryanas, A.P. (2004, May). USAF UAV mishap epidemiology, 1997-2003. Distributed at the Human Factors in Uninhabited Aerial Vehicles First Annual Workshop, Mesa, AZ.
- [56] Della Rocco, P., Cruz, C. and Clemens, J.A. (1999). The role of shift work and fatigue in air traffic control operational errors and incidents (DOT/FAA/AM-99/2). Oklahoma City, OK: FAA Civil Aeromedical Institute.
- [57] Kiekel, P.A., Gorman, J.C. and Cooke, N.J. (2004). Measuring speech flow of co-located and distributed command and control teams during a communication channel glitch. Retrieved August 12, 2005, from [http://www.certt.com/publications/Measuring%20speech%20flow%](http://www.certt.com/publications/Measuring%20speech%20flow%20)

4.3.4 Effects of Control Migration on Concept of Teams

4.3.4.1 Teams Versus Groups

A group refers to a small set of organizational members comprising three to fifteen actors who regularly interact for the purpose of a common goal. All teams qualify as groups; however, all groups do not fulfill the criteria required for classification as a team. Teams are behaviorally distinct from groups on the dimensions of performance requirements, interdependence, and accountability. “A set of two or more individuals who are expected and required to interact dynamically, interdependently, and adaptively to accomplish their goals, but do not are still a team – they are simply an ineffective team” [1]. The existence and prominence of teaming in organizations is a significant distinguisher of organizational structure and culture.

4.3.4.2 Types of Teams

Teams may be classified according to four general structures: traditional work teams, long-term project teams, network design structures, and parallel teams [2]. These structures may be further characterized by formality, temporality, purpose, and membership. Therefore, teams may be distinguished from one another in terms of formal designation within a system, lifespan of the team, tasks and functions, designation of goals, interchangeability of skills, and the extent to which team members possess membership on multiple teams. An additional aspect is the notion of distribution; do team members reside locally or remotely within and/or external to the organization? This is a critical factor because a distributed or virtual team demands highly flexible, coordinated, and specific communication. Watson-Manheim and Bélanger [3] noted the dependence of virtual teams on communication technologies for accomplishing goals, yet these same teams experienced significant problems with communication-based work processes.

As the relationship of human and computer interaction evolves, the notion of what has constituted a human-member team must be changed to include nonhuman entities (e.g., autonomous UMVs). This broadening of relationship definition can still be loosely characterized within the traditional definition of team.

The migration of operator control to autonomous agents is grounded in the need of team entities to achieve mission success. Because teams have greater performance than work groups, this fulfills the criteria of meeting performance requirements. Consequently, optimal mission performance with respect to migration of operator control is dictated by the interdependence of humans and machines. Successful decision making is determined by the cooperation and coordination of all team entities. The third criterion is illustrated by the shared accountability of man and machine in mission success. Have the appropriate exchanges occurred for operator control from human to machine and vice versa?

Successful team function is dependent upon team member collaboration, trust, and technology. One aspect of how communication is important is its role in information behavior. Sonnenwald and Pierce [4] determined the why, what, and how were relevant concepts for group work contexts in C2 environments. "C2 team members need to collect, synthesize and disseminate information to create an understanding of the current battlefield situation and to anticipate future battlefield events". One should also consider the who and when. Therefore, military teams can be understood as functional organisms, coordinating work processes among team actors to achieve macro and micro level system goals within specified timeframes.

Coalition operations require the coordination of dynamic and culturally-diverse teams. Regardless of whether the teams comprise humans, UMV members, or both, the principles of intercultural communication may apply. Cross-cultural differences may present challenges for facilitating intra-team and inter-team coordination. These differences can be evident in team member attitudes and behaviors, and more recently, have been attributed to primary differences in group cognition and behavior [5]. Collectively, these variables can cause undesirable or hazardous behavior during team operations. Team interactions should be structured to manage uncertainty and anxiety for face-to-face and virtual contexts.

4.3.4.3 Distributed and Dynamically Changing Teams

Virtual teams are groups in which the members are geographically distributed but technologically connected to support asynchronous and/or synchronous communication for the purpose of coordinating behavior and goal achievement. In this context, technology platforms are critical foundations for forging network relations and permitting teamwork. Virtual teams provide an organizational structure contrary to the high-level hierarchies of military and government bureaucracies. The result reflects a flattened, lean, fluid, specialized and responsive network.

Qureshi and Vogel [6] identified three types of adaptive social processes virtual teams experience: technological, work, and social adaptation. The adoption of new technologies for communication, the application and integration of technologies to team member ways of working, and the emergence of social norms related to technology affect the way virtual teams adapt to the environment. Virtual teams are communication and technology intensive. "The challenge for virtual teams is in allocating tasks based on knowledge and skill in an environment that is often dispersed across space, time and organizations". This environment is further complicated by the communication demands of culturally-diverse team members. Lee-Kelley, Crossman, and Cannings [7] suggest a "focus on attributes of persons, situational expressions of these attributes and the relation of personal attributes toward others in the work group, may be used to explain some of the relational issues that spatial and temporal separation in the virtual team may create". Managers and organizational designers should consider the additional complexity of cultural diversity and how it impacts relational issues among team members.

In developing communication protocols for UMV teams, the dimensions of virtual organizations proposed by DeSanctis, Staudenmayer, and Wong [8] may be useful. The characterization of space (e.g., spatial dispersion

of organizational members), time (e.g., the degree of asynchronous operation), culture (e.g., norm, value, behavioral variability), and boundary (e.g., organizational dispersion) provides a framework for developing communication standards. As previously noted, virtual teams have similarities when compared with traditional team structures; however, because of the heightened dependency on information communication technology (ICT), understanding the organizational processes at the supra and micro system levels becomes more critical for virtual teams. Only when this knowledge is obtained and observed can virtual teams be effectively and properly supported. For example, the transfer of UMV system control from operator to operator is a team process. By understanding the vigilance issues, the constraints of operator control transfers, and other environmental variables, ICT can be optimally structured.

4.3.4.4 Dimensions of Team Performance

4.3.4.4.1 Organizational Culture and Structure

Organizational processes occur at every system level: the individual components, the environmental context, the system goals, and the organizational resources (e.g., people, technology, etc.). When a keen understanding of the inner workings of a system is established, leaders occupy an educated position to plan and manage change. Ali, Pascoe, and Warne [9] reinforced findings from the literature regarding the role of organizational culture in effective social learning and organizational change. Organizations which sustain an environment of member empowerment, forgiveness, trust, individual and organizational commitment, information sharing, openness of decision-making, and cultural cohesiveness enable effective social learning. Organizations which uphold these values create environments where members are able to engage in quality learning. Open communication is a primary catalyst for achieving organizational learning [10]. “Social control is particularly valuable when the need for sharing tacit knowledge increases over socially impoverished channels of virtual communication, where conflict may escalate due to teamwork issues engendered by cultural difference in communication and problem-solving styles and approaches” [11].

Organizations must maintain high levels of adaptability to achieve an optimal level of survival/success. “An adaptive structure requires organizations to develop dynamic capabilities to modify current practices in response to dynamic changes in the environment” [11]. Many have applied a deterministic approach to communication technology, and view technology as the source of impact in a social network. A social network approach indicates the converse. According to a social construction perspective, the relationship of technology and structure is indicated by a simultaneous affecting of each other [12]; “the composition of content and context are not predetermined by technological design or by the prior existence of certain social groups”.

Cultural differences may exist across team members on the dimensions of learning style, thinking style, teamwork experience, functional expertise, uncertainty threshold, and intelligence (e.g., analytical, practical, and creative) [11]. These differences may create barriers to building trust and consequently retard the development of team cohesion [7]. To further complicate team functioning, language usage can result in inaccurate, ambiguous communication.

High performing virtual teams tend to have members with experience in multicultural environments. “The difficulty of getting a group of disparate people to come together and work effectively cannot be over emphasized” [7]. One approach to managing intercultural communication is to minimize adverse behaviors by building trust among culturally-diverse team members and across teams. “The status report genre, bug/error notification genre, update notification genre, and phone meeting management genre system emerged as key communication structure that both reflected and shaped members’ temporal and work practices” [13].

This reflects the suitability of structuring communication and work processes for improved coordination in distributed teams. The enactment of work routines provides stability for team structures. Team stability is positively affected by homogeneous rules. Heterogeneous rules are associated with increased novelty and team adaptation [14]. Therefore, it is advisable to conceive of the appropriate levels of stability for C2 teams and balance heterogeneous and homogeneous behavioral rules accordingly.

4.3.4.4.2 Satisfaction

The team is important to an organization because its effectiveness determines organizational mission success and member satisfaction. The literature has numerous examples of research supporting the relationship of member satisfaction and member productivity. With the transition to increasingly autonomous UUVs, some might dismiss team member satisfaction as irrelevant. However, as long as HMI is present, satisfaction remains important for the human elements of the team. High satisfaction of team members varies directly with team commitment and committed team members are critical for operational success.

4.3.4.4.3 Qualitative Composition of Teams

Teams are comprised of organizational members; each member presenting emotional, psychological, and behavioral differences. One dimension of personality is the typing of individuals as A or B (TABP). Keinan and Koren [15] established a significant relationship between team member personalities and group performance. "Our findings show that when the task is competitive, the effect of TABP on performance differs from when the task is noncompetitive." Teams primarily comprising type A personalities are directly associated with improved team performance for competitive tasks and are generally more productive than those teams with a majority of type B personalities.

But, the literature is generally contradictory in the area of group composition. For example, homogeneous teams have been reported as both positive and negative on the measure of performance. It has been argued trait similarity increases team member attraction; this positively affects relational satisfaction and team performance. Conversely, research has also documented the positive relationship of dissimilar group membership and team performance. Theoretically, members with varied opinions, knowledge, and experiences will provide a greater quantity of unique problem resolutions resulting in optimal performance for complex environments.

Teams comprising fundamental knowledge, skills, and abilities (KSAs) are better equipped to fulfill mission goals. KSA requirements are not completely transferable from in-person teams to virtual teams and vice versa. The densely computer-mediated communication environment of the virtual realm requires a heightened adeptness at managing digital conflict, text-intensive interactions, and media selection [16].

4.3.4.4.4 Trust

Virtual teams are not immune to the requirements for success that traditional teams face. Team effectiveness is determined by connecting with key team members for information sources (e.g., knowing who to call for specific questions), using appropriate communication media (e.g., e-mail, telephone, listservs, intranets, etc.), and establishing a positive organizational culture. Watson-Manheim and Bérlanger [3] found virtual teams are highly influenced by establishing organizational norms for communication media choice, providing appropriate training, and managing team member relationships.

4.3.4.4.5 *Training*

The literature indicates teamwork does enhance performance; therefore, teams can benefit from focusing on improving member relations. Training is a primary vehicle for creating a positive teamwork environment. This may include building skills in coordination [17]. Team members, human or machine, must acknowledge communication, provide meaningful information at appropriate time intervals, use standardized language, use feedback mechanisms, address conflicts, recognize uncertain and complex environments, and identify problems. Teams will likely benefit from training in conflict management, uncertainty avoidance, learning to select appropriate communication channels, and how to design appropriate messages. Indeed, training is an important and viable component of performance enhancement programs. Stout, Salas, and Fowlkes [1] suggest “that team training equates to providing trainees with necessary KSAs (e.g., team competencies) to engage in cooperative behavior and to efficiently interact with one another to attain effectiveness”. In their study of training effects in complex environments, pilots who were trained in teamwork behaviors were better prepared to deal with complex problems using team competencies.

4.3.4.5 **References**

- [1] Stout, R.J., Salas, E. and Fowlkes, J. (1997). Enhancing teamwork in complex environments through team training. *Group Dynamics: Theory, Research, and Practice*, 1(2), 169-182.
- [2] Cohen, S.G. (1993). New approaches to teams and teamwork. In: *Organizing for the Future: The New Logic for Managing Complex Organizations*, J.R. Galbraith and E.E. Lawler (Eds.), San Francisco: Jossey-Bass Publishers, pp. 194-226.
- [3] Watson-Manheim, M.B. and Bérlanger, F. (2002). Support for communication-based work processes in virtual work. *E-Service Journal*, 1(3), 61-82.
- [4] Sonnenwald, D.H. and Pierce, L.G. (2000). Information behavior in dynamic group work contexts: Interwoven situation awareness, dense social networks and contested collaboration in command and control. *Information Processing and Management*, 36, 461-479.
- [5] Yuki, M. (2003). Intergroup comparison versus intragroup relationships: A cross-cultural examination of social identity theory in North American and East Asian cultural contexts. *Social Psychology Quarterly*, 66, 166-183.
- [6] Qureshi, S. and Vogel, D. (2001). Adaptiveness in virtual teams: Organizational challenges and research directions. *Group Decisions and Negotiation*, 10, 27-46.
- [7] Lee-Kelley, L., Crossman, A. and Cannings, A. (2004). A social interaction approach to managing the “invisibles” of virtual teams. *Industrial Management & Data Systems*, 104(8), 650-657.
- [8] DeSanctis, G., Staudenmayer, N. and Wong, S.S., (1999). Interdependence in virtual organizations. In: C.L. Cooper and D.M. Rousseau (Eds.), *Trends in organizational behavior: Vol. 6*, 81-103, New York: Wiley.
- [9] Ali, I.M., Pascoe, C. and Warne, L. (2002). Interactions of organizational culture and collaboration in working and learning. *Journal of Educational Technology & Society*, 5(2), 60-68.
- [10] Ellinger, A.D. and Bostrom, R.P. (1999). Managerial coaching behaviors in learning organizations. *The Journal of Management Development*, 18(9), 752-771.

- [11] Harvey, H., Novicevic, M.N. and Garrison, G. (2004). Challenges to staffing global virtual teams. *Human Resource Management Review*, 14, 275-294.
- [12] Lea, M., O'Shea, T. and Fung, P. (1995). Constructing the networked organization: Content and context in the development of electronic communications. *Organization Science*, 6, 462-478.
- [13] Im, H., Yates, J. and Orlikowski, W. (2005). Temporal coordination through communication: using genres in a virtual start-up organization. *Information Technology & People*, 18(2), 89-119.
- [14] Walker, C. and Dooley, K.J. (1999). The stability of self-organized rule-following work teams. *Computational & Mathematical Organization Theory*, 5(1), 5-30.
- [15] Keinan, G. and Koren, M. (2002). Teaming up type As and Bs: The effects of group composition on performance and satisfaction. *Applied Psychology: An International Review*, 51(3), 425-445.
- [16] Furst, S., Blackburn, R. and Rosen, B. (1999). Virtual team effectiveness: A proposed research agenda. *Info Systems*, 9, 249-269.
- [17] Leedom, D.K. and Simon, R. (1995). Improving team coordination: A case for behavior based training. *Military Psychology*, 7, 109-122.

4.3.5 Important Issues in Control Migration

4.3.5.1 Interoperability

Implicit in the concept of migration of operator control is the assumption that there is complete interoperability of both systems and personnel. Current work on the NATO UAV interoperability effort (e.g., STANAG 4586) aims to address issues of system interoperability specifically with regards to the data link interface between the control station and vehicle and C2 interfaces between the control station and external command and control, communications, computers, and intelligence (C4I) systems. However, despite these efforts, migration of operator control is currently regarded as one of the most complex and risky phases of UUV operations. For example, many system parameters may be changed and difficult procedural and technical issues can be involved. This phase typically requires meticulous planning and allows almost no flexibility in execution. Migrating control between dissimilar systems is particularly difficult because of issues of system synchronisation. Migration of control between operators and systems at physically dispersed locations may require initiation and alignment of systems, one or more data and communications links, and possibly even cryptological equipment. It may also require coordination with external C2 agencies. This situation may be made more complex if a face-to-face debrief is not possible. Additionally, the control system will need to be designed to allow for system synchronisation and facilitate operators achieving an adequate level of situational and system's awareness so a handover can be safely performed. However, standards and safeguards are particularly lacking for the latter issue.

4.3.5.2 Procedures for Migration of Control

Using the example of current UAV systems, migration of operator control needs to be coordinated prior to the actual event. This means the specific procedures and information to be exchanged should be identified during the mission planning process. The procedures should be available in checklist form and should have been previously validated to minimize the unintended effects of operator input errors as well as be applicable to

both nominal and off-nominal situations. Information exchange can be facilitated by the preparation of a mission folder containing the flight plan, tasking, handover location, datalink parameters (e.g., frequencies and cryptological settings), other system settings, and emergency or contingency plans. Additionally, there needs to be processes implemented to ensure this information is updated to reflect actual mission circumstances. Since migration of operator control demands a high level of crew coordination, all involved personnel should have initial and recurrent proficiency training in control transfer procedures as well as crew coordination. The latter may be particularly applicable for personnel without prior aviation experience. Finally, systems should be designed to provide immediate and unambiguous feedback to operators regarding the state of control transfer, whether gaining or releasing.

4.3.5.3 Team Situational Awareness

4.3.5.3.1 Levels of Situational Awareness

Team situational awareness has been described as the process by which a knowledge-heterogeneous team develops a dynamic shared mental model in accordance with the demands of making predictions about a dynamic team task environment [1]. Recent research has demonstrated in turn that team performance directly correlates with team members' levels of SA [2]. Accordingly, in order to safely migrate operator control, it is imperative the operator gaining control have at least the same level of SA as the operator releasing control [3]. Endsley [4] has described three levels of SA: perception of the elements in the environment (level 1 SA), comprehension of the current situation (level 2 SA), and prediction of the future status of one's own situation and the surrounding elements (level 3 SA). Operators should strive for the highest level of SA (e.g., level 3 SA) prior to assuming control of a UMV [5]. SA may need to be achieved at the system, operational, and mission levels. For a UAV mission, this may include SA of a very broad array of issues to include:

- System status: Fuel status, power settings, active and non-active systems, payload status, settings, etc.
- System degradations: Missing functionality and its consequences for flight continuation, vehicle performance, achievement of mission objectives, etc.
- Datalink status: Coverage, frequencies, cryptological settings, antenna alignment, etc.
- Vehicle parameters: Position, speed, attitude, intentions, and future flight path.
- Airspace: Restricted areas, danger zones, and both current and predicted weather.
- Position of other elements in the environment: Traffic, threats, cooperative elements, and coalition assets as well as their intentions and predicted future status.
- Mission objectives: Tasking(s), commander's intent, target information, downstream user requirements, intelligence situation and prognoses, etc.

Obviously, level 1 SA is easier to obtain and requires less effort than level 3 SA. However, the more complex the situation, the more important it becomes to achieve level 3 SA, and thus the more complicated the process for migration of operator control.

4.3.5.3.2 Sharing Situational Awareness

Current research has yielded conflicting results on the existence of detrimental effects of geographic dispersion on team processes, team knowledge, and team situational awareness. However, co-located teams appear to more readily carry out planning and adaptive behaviours and generally communicated more than distributed teams [6]. Consequently, it appears important to facilitate information sharing during UMV

handoffs, which may be accomplished in several ways. It can involve voice communication, text message exchange, graphical display exchange or alignment of system information (including graphics and status). The human interaction in these exchanges can vary greatly. However, this is also true of the potential for human error during the exchange. The more complex the situation, the more operators will have to rely on automation to help them attain SA considering control transfers have to be performed within a certain timeframe. Therefore, there is a need to design the HMI for the operator in such a way to minimize the workload during transfer of control. As an example it could help the operator to focus the attention to changed mission folder items compared to the original situation.

4.3.5.4 Priorities in Sharing Information

Teams need environments which facilitate efficient and effective C2 information sharing. Communication principles for data and knowledge exchanges can be applied at the human and human-computer levels in C2 contexts. Information priorities may be classified in a communication taxonomy for UUV operator teams. When team members trust each other and the team infrastructure, are educated about organizational structure and processes, and understand information processing, fluid communication is enabled.

Teams will likely benefit from training in information salience, conflict management, uncertainty avoidance, learning to select appropriate communication channels, how to design appropriate messages. Team members should be advised on the relationship of communication to relationship building within dynamic, complex, and stressful situations. Indeed, team members need to quickly identify individual and team information needs, fulfill the needs, and disseminate, synthesize, and integrate that knowledge into mission activities. Consequently, situational awareness requirements can be addressed by supporting social networks with access to databases, human capital, and technology.

4.3.5.5 References

- [1] Cooke, N.J., Stout, R. and Salas, E. (2001). A knowledge elicitation approach to the measurement of team situation awareness. In: M. McNeese, E. Salas and M.R. Endsley (Eds.), *New Trends in Cooperative Activities: Understanding System Dynamics in Complex Environments* (pp. 114-139). Santa Monica, CA: Human Factors and Ergonomics Society.
- [2] Cooke, N.J., DeJoode, J.A., Pedersen, H.K., Gorman, J.C., Connor, O.O. and Kiekel, P.A. (2004). The role of individual and team cognition in uninhabited air vehicle command-and-control (AFRL-SR-AR-TR-04-0220). Mesa, AZ: Arizona State University East.
- [3] Theunissen, E., Goossens, A.A.H.E., Bleeker, O.F. and Koeners, G.J.M. (2004, August). UAV mission management functions to support integration in a strategic and tactical ATC and C2 environment (AIAA 2005-6310). Presented at the AIAA Modeling and Simulation Technologies Conference and Exhibit, San Francisco, California.
- [4] Endsley, M.R. (2000). Theoretical underpinnings of situation awareness: A critical review. In: M.R. Endsley and D.J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 3-32). Mahway, NJ: Lawrence Erlbaum.
- [5] Goossens, A.A.H.E., Koeners, G.J.M. and Theunissen, E. (2004). Development and evaluation of level 3 situation awareness support functions for a UAV operator station. Proceedings of the 23rd Digital Avionics Systems Conference. Retrieved August 24, 2005, from http://www.synthetic-vision.tudelft.nl/SVatDelftUofT/publications/DASC2004_UAV.pdf

- [6] Cooke, N.J., DeJoode, J.A., Pedersen, H.K., Gorman, J.C., Connor, O.O. and Kiekel, P.A. (2004). The role of individual and team cognition in uninhabited air vehicle command-and-control (AFRL-SR-AR-TR-04-0220). Mesa, AZ: Arizona State University East.

4.3.6 Future Challenges

Teams play a critical role in complex military operations necessitating multi-operator environments [1]. Although one project evaluating teams in a UAV C2 environment found no performance differences between co-located and distributed teams, subtle differences in team processes and individual task knowledge were found suggesting the equivalence in team performance was achieved via modified team process strategies [2]. As Cooke et al. noted [2], “these results begin to suggest the importance of considering long-term process behaviors that can accrue over time ultimately impacting team performance in [a] command and control task”. Unfortunately, the limited empirical evidence to date on team performance in distributed environments presents a significant challenge in itself. Thus, the potential future challenges posed by migration of operator control in UUVs can best be anticipated by looking to the current state of knowledge in the fields of team processes and team communications.

The presence of interpersonal and task conflict may be perceived as negative; however, its relation to team performance is a positive, direct relationship. For example, intragroup task conflict creates opportunities for team members to better understand a problem through team discussions. As a result, team members are more likely to voice dissenting or novel opinions. To balance and maximize the useful exchange of ideas in team processes, it is advisable to accept a moderate level of task conflict, but to train members in conflict management techniques or to create a problem solving protocol. A moderate level of task conflict tends to be positively associated with team commitment, solution satisfaction, team trust, and enhanced performance.

Interpersonal conflict refers to value, goal, or need differences among organizational members. This type of conflict is frequently characterized as a personality incompatibility. This negatively affects team trust and performance. In this conflict, member focus is directed to non-productive behaviors and stress and emotion levels are heightened. Again, team training in interpersonal communication skills may be valuable for avoiding and minimizing this type of conflict.

Alternatively, performance feedback may moderate group task conflict, where past issues involved in group activities are revisited as a result of the feedback. For example, teams with positive relations tend to recover and build on negative performance feedback. Teams with the same performance feedback and a history of negative relations, however, tend to further degrade in quality of interactions and performance.

As part of the restructuring of military hierarchies to self-organizing teams, it may be advisable to move away from a process-outcome view of groups. Peterson and Behfar [3] suggest “teams are at particular risk of experiencing extremely high relationship conflict and poor future performance when two conditions are simultaneously met; teams that do not establish trust before they receive negative feedback are especially vulnerable to ongoing relationship conflict, and likely to perform poorly”.

Ideally, team members should manage the intensity level of the conflict. Balance the benefits of increased critical reasoning by allowing a minimal level and avoiding the negative impact of destructive team interactions at high intensity conflict. De Dreu and Weingart [4] “support the information processing perspective that suggests that whereas a little conflict may be beneficial, such positive effects quickly break down as conflict becomes more intense, cognitive load increases, information processing is impeded, and team performance suffers”.

Much of the literature is based on qualitative, self-report data. The dramatic consequences in the C2 environment require building upon the findings of case studies and building experimental evaluation of those observations concepts. Organizational leaders need to evaluate the social norms, behavioral norms, cultural norms of team members, task work, and team goals within the context of dynamic environments to better structure, support, and develop team operations. In a virtual team environment, operational protocols can be designed in accordance with the unique characteristics and requirements of the team members. The behavioral tendency for a performer to allocate attention from concurrent tasks to the high priority task to maintain standards of performance [5] is valuable information for communication system design. For example, verbal interactions among remote and co-located participants were found to be significantly retarded when participants were engaged in challenging tasks [6]. There were no significant differences in task SA and performance for the remote and in-person communicators; however, verbal communications degraded SA for both conditions.

Some general recommendations to consider for future work and research include:

- Conceptualize work process and structure as sequences of communicative actions which coordinate the activities of members [7,8].
- Develop trust and cohesion by incorporating face-to-face meetings early in the team creation process.
- Organizational roles should be clearly defined across team members/agent and task responsibilities at the individual level (human and technology).
- Evaluate which tasks are appropriate for virtual teams.
- Tasks should be clearly communicated and unambiguous. For complex tasks, provide access and availability for increased communication and collaboration.
- Create ways for social ties to be nurtured in virtual teams.
- Provide training for team members in communication skills:
 - Interpersonal,
 - Organizational,
 - Intercultural,
 - Uncertainty reduction,
 - Communication protocol development/use, and
 - HMI communication.
- Develop communication protocols which reflect environmental contexts, media constraints, information complexity, task and socially-related interactions, and technological capabilities.
- Develop systematic, empirical research programs to test the behavior of human and human-machine virtual teams in C2 environments. This data is important for determining appropriate cultural and structural changes to allow co-located and virtual teams to succeed.

Additionally, McCarley and Wickens [9] reviewed the literature and summarized current UAV specific human factors research shortfalls, several of which are directly applicable to the topic of migration of operator control in UUVs:

- Develop and test formal procedures for the transfer of control between teams of operators.
- Develop and test HMIs, automation, and procedures to ensure operators have adequate system awareness when assuming vehicle control.

- Delineate circumstances under which responsibilities for vehicle and payload control may be safely performed by a single operator versus circumstances where responsibility should be distributed over two or more operators.
- Delineate circumstances where a single operator can safely simultaneously control multiple UMVs.

The potential benefits and promise offered by UMVs in a multitude of applications have captured the attention of both the military and commercial sectors. When technology changes rapidly or new and radical designs are introduced, previous human factors data may no longer be valid. It is therefore imperative to address the human factors and teaming issues arising from the advent of migration of operator control so the full potential of UMVs is realized. It should be obvious that rather than eliminating human factors concerns, UMVs have instead opened a new and critical chapter in human factors research.

4.3.6.1 References

- [1] Salas, E., Cannon-Bowers, J.A., Church-Payne, S. and Smith-Jentsch, K.A. (1998). Teams and teamwork in the military. In: C. Cronin (Ed.), *Military Psychology: An Introduction* (pp. 71-87). Needham Heights, MA: Simon & Schuster.
- [2] Cooke, N.J., DeJoode, J.A., Pedersen, H.K., Gorman, J.C., Connor, O.O. and Kiekel, P.A. (2004). The role of individual and team cognition in uninhabited air vehicle command-and-control (AFRL-SR-AR-TR-04-0220). Mesa, AZ: Arizona State University East.
- [3] Peterson, R.S. and Behfar, K.J. (2003). The dynamic relationship between performance feedback, trust, and conflict in groups: A longitudinal study. *Organizational Behavior and Human Decision Processes*, 92, 102-112.
- [4] De Dreu, C.K.W. and Weingart, L.R. (2003). Task versus relationship conflict, team performance, and team member satisfaction: A meta-analysis. *Journal of Applied Psychology*, 88(4), pp. 741-749.
- [5] Wickens, C.D. (1980). The structure of attentional resources. In: R. Nickerson (Ed.), *Attention and performance VIII* (pp. 239-257). Hillsdale, NJ: Erlbaum.
- [6] Gugerty, L., Rakauskas, M. and Brooks, J. (2004). Effects of remote and in-person verbal interactions on verbalization rates and attention to dynamic spatial scenes. *Accident Analysis and Prevention*, 36, 1029-1043.
- [7] Yuki, M. (2003). Intergroup comparison versus intragroup relationships: A cross-cultural examination of social identity theory in North American and East Asian cultural contexts. *Social Psychology Quarterly*, 66, 166-183.
- [8] Yates, J. and Orlikowski, W.J. (2002). Genre systems: Structuring interactions through communicative norms. *Journal of Business Communication*, 39(1), pp. 13-35.
- [9] McCarley, J.S. and Wickens, C.D. (2005). Human factors implications of UAVs in the national airspace. Retrieved July 30, 2005, from <http://www.humanfactors.uiuc.edu/>

4.4 MANPOWER AND SKILLS

4.4.1 Selecting UMV Crews

4.4.1.1 Introduction and an Alternative Crew Selection Method

As part of System of Systems and the Human Factors of Command and Control, personnel selection must be considered. This assumes that humans will always be part in the command and control of UMVs at some level of abstraction.

UMVs are new technologies for most militaries around the world, and potentially require new jobs, positions, occupations, and units to command and control these assets. On the other hand, militaries have similar manned vehicles with similar payloads. The personnel that operate these vehicles are highly skilled and knowledgeable, and these skills and knowledge are potentially transferable to operating UMVs. Moreover, if UMVs were highly “intelligent” or “autonomous” then perhaps only general skill and knowledge levels would be required to operate the vehicles and their payload. The transfer of skills and knowledge, and the requirement for general skill and knowledge levels will contribute to Force Multiplication by drawing from an existing, broader pool of people that can operate UMVs.

For example, a pilot, a tank driver, and an Officer Of the Watch might be well suited to fly, drive, and sail UAVs, UGVs, and USVs, respectively. These are positions with the expected high level of expertise. Moreover, a navigator, a gunner, and an Operations Room Officer may have enough general skill and knowledge to be able to quickly become expert UMV operators.

The Canadian Forces Experimentation Centre (CFEC) is exploring a new method for selecting crews that involve matching tasks and knowledge statements within a Canadian Forces – wide task and knowledge database to predicted tasks and knowledge statements derived from a composite scenario that involves the new technology – in this case, multiple UAVs. As more matches that are made for each position in the database, the more likely that that position or occupation would perform well as part of the crew for that UMV. This method represents a substantial departure from common crew selection methods that are often based on career progression, legal considerations, availability, and ownership of the new asset. The new method has four steps as follows:

- 1) Decompose a composite scenario involving new technologies into a hierarchy of goals.

There are many techniques to perform mission analysis and function decomposition (e.g., MIL HDBK 46855). The technique used in this case is based on Perceptual Control Theory applied to function and task decomposition [1]. The result is a Hierarchical Goal Analysis (HGA) where the scenario is described in terms of desired system goals. At some level of the hierarchy, the goals are assigned (allocated) to humans and machines. Further research is required to systematically develop individual jobs based on predicted workload and/or grouping tasks into roles and responsibilities.

- 2) Propose and link the new job elements (task and knowledge statements) to the goals.

Job elements can be associated with the completion of those goals assigned to humans. The job elements are not limited to task and knowledge statements, but may include the other elements (such as intelligence, aptitude, personality, health, gender, etc.) depending on the level of fidelity required. However, there are some indications that current tasks may be a first order predictor of new job performance.

- 3) Compare the new job elements to the CF job element inventory.

This methodology for selecting crews depends on having a task and knowledge statement inventory so that the new task and knowledge statements can be compared to those in the inventory. The mathematical equation for the comparison has been referred to as a Job Similarity Index (JSI). The simplest matching algorithm, or JSI, is as follows:

$$JSI = \frac{1}{2} \frac{\text{number inventory tasks that match new tasks}}{\text{total number of new tasks}} + \frac{1}{2} \frac{\text{number of inventory knowledge that match new knowledge}}{\text{total number of the new knowledge}}$$

As JSI approaches one, then the current job would match the new job. The hypothesis is that the job performance is directly related to the JSI value. That is, those personnel who have a high JSI will perform well in the new job and will require minimal training, since they perform most of the tasks in their current job and have most of the knowledge from their current job that are required for the new job.

- 4) Select positions based on the best match.

4.4.1.2 Experimental Design

CFEC conducted an experiment to evaluate this crew selection method and to determine whether JSI predict job performance. Military participants were asked to participate in a 6-hour experiment that involved the command and control of five UAVs in support of an intelligence, surveillance, and reconnaissance mission as the UAV crew searched for a terrorist boat amongst 14 other fishing boats of a similar classification.

Each participant provided demographic information as well as wrote the Wonderlic General Cognitive Ability (GCA) test. The participant performed a one-hour UAV mission in DRDC – Ottawa's synthetic UAV Research Test Bed: 20 minutes in each position as the Vehicle Operator (VO), Payload Operator (PO), and Mission Commander (MC). Two other experimental staff members played the alternate positions, thus a crew of three was formed. Following the first run, training was conducted in the form of a question and answer period. A proficiency test was administered, and then the participant repeated the hour scenario again. The measured variables included demographic information, GCA, task completion, assessed performance, Situational Awareness, and proficiency test results, while JSI was calculated using the above formula for each participant.

The primary performance measures were subjective observations about a number of tasks. Two observers rated performance on the task from one (low) to five (high). A zero meant that the task was not performed. Another measure of performance was a situational awareness (SA) map tasks where the subject was asked to recall the friendly, neutral, unknowns, and unfriendly radar returns and draw them on a map. Their answers were compared to ground truth, and high scores were given when the two maps were similar.

The data analysis was designed to show whether performance and JSI are related. Figure 4-5 is a fictitious example showing the scatter of data. Excel™ was used to calculate trendlines as well as the normalized mean distance (m.d.) between the data points and the trendline. If the trendline has a positive slope, then performance and JSI are related. If the slope is zero, then there is no relationship. If the slope is negative, then the two variables are inversely related. As the mean distance approached zero, then the points would fall onto the trendline and there would be high confidence that the data and the trendline were correlated. As the mean distance approached 100% of the maximum possible mean distance then there would be low confidence that the data and trendline were correlated. Note that this is a preliminary analysis in order to obtain generic impressions of the variables' relationships.



Figure 4-5: Anticipated Results Showing that Performance is Directly Related to JSI.

4.4.1.3 Results and Discussion

Figure 4-6 shows the preliminary results in graphical form. The first graph indicates that task completion does not depend on JSI. That is, all participants were able to complete 97.7% of the UAV tasks regardless of the percentage of tasks and knowledge they had in their current occupations. The mean distance between the trendline and the data was 1.3%, which gives us a very high degree of confidence that the data are correlated with the trendline.

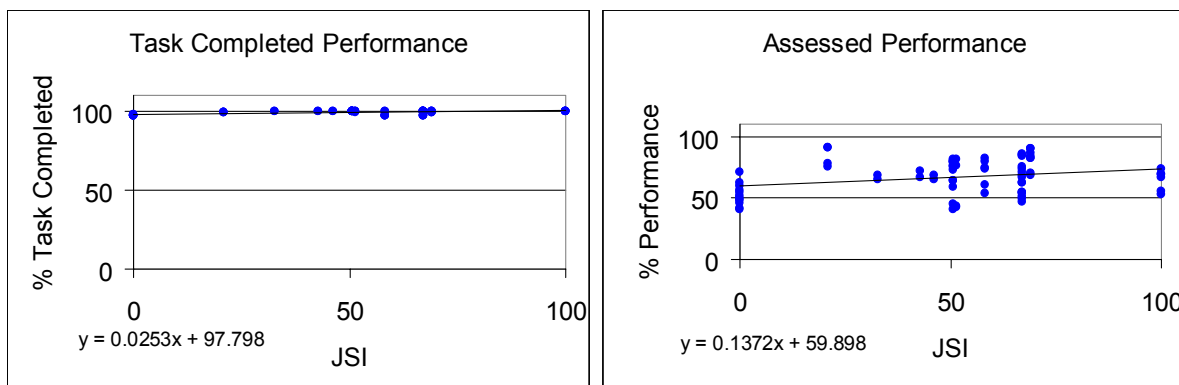


Figure 4-6: JSI versus Performance Results.

The second graph indicates a slight positive relationship between JSI and the assessed performance results (i.e., slope = +0.13). However, our confidence that the data and trendline are correlated is lower because the mean distance increases to 10%. Note that the intercept value is 59.9%. That is, even participants who do not perform any of the UAV tasks or have any of the required UAV knowledge, still have a general level of tasks and knowledge that they can achieve 60% performance. Anecdotally, only after several minutes of training on the system, the performance rises (training proficiency test average mark = 74.2%). Also, the other two crew members (a private and a corporal) became experts at all the positions well within 3 hours. Clearly, this simple composite scenario required a general level of tasks and knowledge in order to achieve adequate performance. (N.B. the scenario was validated by experienced CF Aurora crew members whose job is maritime surveillance and reconnaissance).

Table 4-1 summarizes the relationships between JSI and other variables measured in this experiment, and Table 4-2 summarizes the relationships between the variables and assessed performance. A detailed analysis would require a multiple regression as well as a test for significance. Also, one must determine the minimum slope value by which it can be said that JSI is related to performance, as well as the maximum mean distance that would still indicate a high confidence level. Never-the-less, there are indications that JSI predicts performance to some degree. However, this scenario was simple enough that a broader pool of participants with general tasks and knowledge could complete 97.7% of the tasks at a performance level of least 60% with minimal training and a fairly robust human-computer interface.

Table 4-1: JSI versus Measured Variables

x-axis	y-axis	Slope	Intercept (%)	Mean distance (%)
JSI	Reference	0	100	0
JSI	Proficiency Test	-0.14	81.2	14.7
JSI	Situational Awareness	-0.10	60.3	16.1
JSI	Task completed	0.03	97.9	1.3
JSI	GCA	0.08	49.2	6.9
JSI	Assessed Performance	0.14	59.9	10.0
JSI	Years of Service	0.19	21.1yrs	11.0
JSI	Service	NA	NA	NA
JSI	Reference	1.00	0	0

Table 4-2: Measured Variables versus Assessed Performance

x-axis	y-axis	Slope	Intercept	Mean distance (%)
Reference	Performance	0	100	0
Years of Service	Performance	-0.28	73.0	11.5
Proficiency Test	Performance	0.06	62.3	11.7
JSI	Performance	0.14	59.9	11.1
Service	Performance	0.15	57.1	10.6
Situational Awareness	Performance	0.39	46.1	9.7
GCA	Performance	0.48	41.2	11.0
Reference	Performance	1.00	0	0

4.4.1.4 Concluding Remarks

There are indications that JSI can be used to predict job performance to some degree. However, there are other factors that influence job performance including the simplicity of the job in combination with a good human-computer interface. As UMVs become more “intelligent” (i.e., operating at high levels of automation), then operators will only need a general level of job elements in order to work the systems at relatively high performance levels. The results seemed to indicate that, depending on the scenario and equipment used, one could select from a larger population of current military personnel.

The alternative method for crew selection is not tied to any particular application, and is hoped to be an objective way of selecting crews particularly when no job incumbents exist. This would be the case for most UMV systems coming online. As countries world-wide begin to build their UMV units, they will need a method for staffing the units either with existing personnel or new recruits if specific skill sets are not found within the organization. The method yields task and knowledge statements for a given scenario, yet the method itself can be applied to any scenario.

The method requires an existing database for the task and knowledge statement lexicon for step 3. That is a common lexicon for tasks and knowledge statements is required. Even between environments (air, land, and sea) a single task may have several meanings. For example, secure a building may mean surround the building with troops for army personnel, close all doors, windows, and hatches for navy personnel, and purchase or lease a building for air force personnel. Initial discussions have started in developing an Intelligent Agent solution that would help “translate” between environments’ lexicons. The next step would be to expand the tool so that it could “translate” between interagency and multi-national task and knowledge lexicons, if they existed.

This study showed that the operator to vehicle ratio is moving in the desired direction for Force multiplication. That is, the operator to vehicle ratio in this case was 3 to 5, and the operators only required a general level of task, skills, knowledge, and training. In the absence of incumbents for UMVs, this crew selection method promises to be a viable alternative that would cross not only environmental boundaries, but also multi-national and interagency boundaries. Thus the method is compatible with system of systems and interoperability thinking.

4.4.1.5 References

- [1] Farrell, P.S.E. and Chéry, S. (1998). PTA: Perceptual Control Theory Based Task Analysis. In: Proceedings of the 42nd meeting of the Human Factors and Ergonomics Society, Chicago, Illinois, October 1998.

4.5 UNINHABITED MILITARY VEHICLE OPERATOR TRAINING

4.5.1 Training of Decision Making Skills Based on Critical Thinking

An important aspect of decision making skills in real-world situations how to decide on a course of action even though available information may be uncertain or incomplete, or relevant information is simply missing. Since there typically are no clear cut answers in situations like this, any augmentation of the decision-making process in the form of training has to focus on how the decision makers interpret the information at hand. For example, how to consider the relevant factors, make plausible assumptions, and identify conflicts in the information. Several studies have shown that these decision-making processes can be augmented by improving the decision makers’ critical thinking for self-critiquing, through training [1] and decision support systems [2].

There are several theories of critical thinking, but the one of most interest here is critical thinking as a dialogue that has been developed by Marvin Cohen and associates in a series of papers [3,4,5]. According to their theory, critical thinking is a series of questions and answers that serves to investigate alternative positions of what the available information may indicate. Three roles are involved:

- 1) The proponent who defend a position by introducing more reasons that are only consistent with the current position;

SYSTEM OF SYSTEMS

- 2) The opponent who asks for missing reasons or introduce rebuttals that cancels reasons or their effect on the conclusion; and
- 3) The facilitator who regulates the process in terms of the relevance of reasons and whether the dialogue achieves the overall goals [4,5].

Often, the opponent tries to expose uncertainties in the proponent's position which may be incomplete when some relevant reasons are missing [3]. The reasons that the proponent introduces as a response to the incompleteness may then conflict with existing reasons by also supporting alternative positions. One or several reasons must then be revoked or assessed in terms of reliability since only one position can be chosen. Thus, the critical dialogue between the proponent and opponent encourages introduction of reasons that have not yet been considered by the other. These reasons are then used to assess positions in terms of their plausibility, correspondence between reasons and observations, coherence of reasons, and the uncertainty of the position based on the number of alternative possibilities where the position would be incorrect [5]. Consequently, the decision quality improves over time as the partners learn more about the positions' strengths and weaknesses. The critical dialogue is applicable to both team and individual decision-making by switching between the roles [6].

An important aspect of the critical dialogues is that they can be adapted to the available time until a decision has to be made. There are several dialogue types, such as persuasion, inquire, information seeking, negotiation, deliberation, and eristic [7], that vary to which extent assumptions are questioned. The decision makers can therefore control the amount of questioning and number of possibilities to consider by choosing the best dialogue type depending on the context. Since the critical dialogues uses the available information within the constraints of the situations, there is no conflict with the assertiveness and rapid responses that is often required in military domains [4]. Should the decision makers be in severe time pressure, they may also choose to adopt a more recognitional decision making strategy instead of using critical thinking [8]. The ability to adapt the decision process depending on the context is often an important aspect of expertise. For example, studies by Freeman, Cohen, and Thompson [9] and Cohen, Adelman, and Thompson [10] show that experienced commercial airline pilots adapt their decision process for diversion to an alternate landing site depending on the available time and uncertainty about the need for diversion. Less experienced pilots did not show the same responsiveness.

Training of critical thinking attempts to encourage a dialogue that clarifies disagreements and weaknesses in positions. For example, Cohen et al. [5] describe a training program that explains the three roles, how to perform a critical thinking dialogue (adapted from von Eemeren and Grootendorst [11]), and general rules that encourages a critical dialogue. After first developing their own positions, the teams identify important disagreements and how to resolve them by challenging, defending, and modifying positions until the parties agree or there is no more time for discussion. The effect of the training program was investigated using Army officers that performed tactical decision making games. The critical thinking training increased the generation of new options and the number of reasons for positions. A similar type of training program has also been evaluated for situation assessment of enemy intent [1,12], and planning of a course of action for tactical decision-making games [10]. This training is based on the improving the coherency of stories that explains the available information. The training consists of four segments for story creation and evaluation, characteristics of task specific stories, how to manage conflicts and generate alternative interpretations, and when critical thinking is appropriate. Mental strategies, such as the Devil's Advocate or the infallible crystal ball, are used to encourage critical examination of positions and reasons. These critical examinations occur naturally in the critical dialogue due the different roles. Overall, the training increased the usage of relevant information and identification of conflicts and assumptions that required further investigation. These changes in the decision

process often improved the final decision. The positive effects of critical thinking training are not surprising since many aspects of the training are based on differences between how experienced and less experienced officers handle similar types of situations [12]. Similar effects of experience have also been found for how commercial airline pilots evaluate options for diversion due to bad weather [9,10]. In addition to adapting the decision process depending on the available time, experienced pilots also requested more information to address sources of uncertainty. Although Cohen, Adelman and Thompson [10] propose a strategy for training critical thinking skills of commercial airline pilots, no training program has been developed or evaluated for option evaluation, however. Finally, the training can be administered using conventional presentations or self-administered individual homework assignments and use advanced simulation techniques for illustration of scenarios.

The preceding discussion shows that critical thinking can enhance decision making in many domains where there is only partial and uncertain information. It is therefore reasonable to expect that critical thinking will also be important for control UMVs when they are employed tactically as a part of or in close cooperation with manned forces. While lower costs and reduced risks for military personnel make UMVs suitable for the dull, dirty, and dangerous missions, they also have several characteristics that affect their operation. Critical thinking appears to be a useful approach for assessing how these characteristics can affect mission accomplishment within the current context. Table 4-3 summarizes a brief review by Svenmarck [13] of some critical characteristics that may be important for control of UMVs. One important characteristic of UMVs that is often mentioned in the literature is the lack of situation awareness from the limited field-of-view of sensor information for control of tele-operated vehicles. The result is often spatial disorientation, lack of awareness of surrounding obstacles, and difficulty of interpreting the overall situation. Further, tele-operation for navigation and control of the sensor suite are in reality separate tasks that can not be performed simultaneously [14]. Both tasks are also hampered by the significant time delays in communicating sensor information and control commands [15]. The combination of tracking difficulty and a preference for endurance typically makes UMVs slower than manned systems. Often, several operators are therefore required to control and manage the UMVs due to the demands on attentional and cognitive resources. Overall, however, the demands are considerably less than when performing the same missions manually without UMVs, which improves the endurance. The effect of these characteristics versus the benefits of less risks and efforts of military personnel can only be assessed by the operator using the available information about the situation. Consequently, a reliable decision making process, such as critical thinking, is essential for maintaining control of UMVs.

Table 4-3: Summary of Characteristics that Affect how UUVs are Employed Depending on the Mission Context – the characteristics are listed as a relative comparison of performing missions with UUVs vs. without UUVs

Pros	Cons
<ul style="list-style-type: none"> • Costs less than military personnel • Can perform more risky missions • More precise weapons management • Less physically and mentally exhausting for operators 	<ul style="list-style-type: none"> • Provide limited information • Time-delay in control and sensor information • Tele-operation requires attentional and cognitive resources • Tele-operation often require more than one operator • Limits interpretation of the situation • Vulnerable • Have a higher failure rate • Not optimised for stealth • Can be slow to deploy • Vehicles that are not fully automated must remain within radio coverage for control. Currently, the radio coverage is often limited, especially in built-up areas • The radio communication is vulnerable to detection and electronic warfare

4.5.1.1 References

- [1] Cohen, M.S., Freeman, J., Wolf, S. and Militello, L. (1995). Training metacognitive skills in naval combat decision making (Technical Report). Arlington, VA: Cognitive Technologies, Inc.
- [2] Freeman, J.T. and Cohen, M.S. (1998). Effects of decision support technology and training on tactical decision making. Proceedings for the 1998 Command and Control Research and Technology Symposium, June 29 – July 1, Monterey, CA: Naval Postgraduate School.
- [3] Cohen, M.S., Freeman, J.T. and Wolf, S.W. (1996). Metarecognition in time-stressed decision making: Recognizing, critiquing, and correction. Human Factors, 38(2), 206-219.
- [4] Cohen, M.S., Salas, E. and Riedel, S. (2002). Critical thinking: Challenges, possibilities, and purpose (Technical Report). Arlington, VA: Cognitive Technologies, Inc.
- [5] Cohen, M.S., Adelman, L., Bresnick, T.A., Marvin, F., Salas, E. and Reidel, S. (2004). Dialogue as medium (and message) for training critical thinking: An initial test. In: R. Hoffman (Ed.), Expertise Out of Context. Mahwah, NJ: Lawrence Erlbaum.
- [6] Walton, D.N. and Krabbe, E.C.W. (1995). Commitment in dialogue: Basic concepts of interpersonal reasoning. Albany: State University of New York Press.
- [7] Walton, D.N. (1998). The new dialectic: Conversational contexts of argument. Toronto: University of Toronto Press.

- [8] Klein, G. (1993). A Recognition-Primed Decision (RPD) model of rapid decision making. In: G.A. Klein, J.R. Orasanu, R. Calderwood, and C.E. Zsombok (Eds.), *Decision making in action: Models and methods* (pp. 138-147). Norwood, NJ: Ablex.
- [9] Freeman, J.T., Cohen, M.S. and Thompson, B.T. (1998). Time-Stressed Decision-Making in the Cockpit. *Proceedings of the Association for Information Systems 1998 Americas Conference*, Baltimore, MD.
- [10] Cohen, M.S., Thompson, B.B., Adelman, L., Bresnick, T.A., Shastri, L. and Riedel, S.L. (2000). *Training critical thinking for the battlefield. Volume II: Training system and evaluation*. Arlington, VA: Cognitive Technologies, Inc.
- [11] van Eemeren, F.H. and Grootendorst, R. (1992). *Argumentation, communication, and fallacies: A pragma-dialectical perspective*. Mahwah, NJ: Lawrence Erlbaum Associates.
- [12] Cohen, M.S., Freeman, J.T. and Thompson, B.T. (1998). Critical thinking skills in tactical decision making: A model and a training strategy. In: J. Canon-Bowers and E. Salas (Eds.), *Decision-Making under stress: Implications for training & simulation*. Washington, DC: American Psychological Association Publications.
- [13] Svenmarck, P. (2005). The role of critical thinking for control of uninhabited military vehicles (UMVs). *Proceedings of the 1st International Conference on Augmented Cognition jointly with the 11th International Conference on Human-Computer Interaction*, Las Vegas, July 22-27, CD-ROM.
- [14] Burke, J.L., Murphy, R.R., Coovert, M.D. and Riddle, D.L. (2004). Moonlight in Miami: an ethnographic study of human-robot interaction in the context of an urban search and rescue disaster response training exercise. *Human-Computer Interaction*, 19(1&2), 85-116.
- [15] Gawron, V.J. (1998). Human factors issues in the development, evaluation, and operation of uninhabited aerial vehicles. *AUVSI '98: Proceedings of the Association of Uninhabited Vehicle Systems International*, 431-438.

4.5.2 Embedded Training for UMV Crews

4.5.2.1 Introduction

Earlier in this SoS chapter, it was stressed that Network Centric Capabilities interweaving sensors, humans and decision aids will increase sources and quantities of information. These advances will place heightened cognitive demands on UAV operators performing C2 tasks. While the C2 structure for the future battle space may not be different from current operations, the ability to fluidly push and pull information over long endurance missions is vastly improved. This poses new challenges for teamwork in UAV operations, particularly when it comes to migration of operator control, team co-ordination and co-operation, team situation awareness and sharing of information. These challenges emphasize the need for novel training concepts for UAV crews.

One of the concepts that emerged from social psychology is training of team decision-making using the 'critical thinking' paradigm [1], which was dealt with in the previous paragraph. In the current paragraph, a human systems engineering approach to team training is dealt with, proposing Embedded Training (ET) as a possible solution. ET for UAV crews basically addresses the aforementioned challenges encountered in teamwork by providing a team training environment that matches the conditions of the future battlefield,

using the actual UAV system in combination with virtual features of the environment, such as threats, targets and other players.

During deployment of a single tactical or strategic UAV system (which may contain more than one air vehicle) for ISTAR type missions typically a team of 50 personnel (in the order of magnitude) is involved in the sustained operation. These personnel consist of operations personnel (mission commanders, air vehicle operators, payload operators, data analysts), maintenance personnel and command personnel, who work in shifts to maintain a continuous operation. For the purpose of ET we will mainly concentrate on what we call the core team. The core team consists of those operators that are responsible for mission C2 tasks and planning, air vehicle control, payload operation and immediate data analysis. More loosely defined we can say that the core team is active during the mission and present in a Ground Control Station (GCS) or in a GCS collocated with a data analysis cell. The core team's primary purpose is guaranteeing mission effectiveness and safety.

Each of the core team members has a specific role and a dedicated working position in the GCS or data analysis cell. For operational training of the core team members it may seem attractive at first sight to be attainable to train the skills, knowledge and attitudes (SKAs) for the separate roles, using specialized training for each role. However, the effectiveness of the core team as a whole depends to a large extent on the teamwork of the members, more than on individual SKAs. This is not hard to understand, since the dynamics of ISTAR type missions require a precise co-ordination between mission planning, air vehicle control, payload operation and image analysis/interpretation. Therefore emphasis should be placed on training the SKAs that are associated with teamwork.

In a typical scenario, the mission commander indicates the points of interest and their priorities, and takes into account the tactical situation and safety constraints. Eventually this results in a mission plan, consisting of a flight plan and sensor plan. The air vehicle operator controls the air vehicle according to the flight plan and the payload operator controls the on-board sensors according to the sensor plan. Data-analysts (photo interpreters, SAR analysts or ELINT analysts) analyze, interpret and report the data to further echelons. Since each on-board sensor has an optimum flight profile and altitude, the use of a specific sensor has consequences for the flight path of the air vehicle and vice versa. During the flight the operators have to deal with unplanned situations such as threats to the air vehicle, changing weather conditions, military and civil air traffic, targets of opportunity, changes in the target list and 'sensor-to-shooter' co-ordination, including communications with other entities in the network. Consequently, the mission plan must be frequently adapted while the air vehicle is in-flight, again requiring co-ordination between the operators.

Teamwork is particularly important under high task load or in situations with a large uncertainty. Inefficient and ineffective team co-ordination under those circumstances can severely impair mission success and safety. It can be expected that the frequency of task load peaks will increase in the future, since there is clear pressure on lowering the operator-to-vehicle ratio. Also, when the UAV is part of a time-sensitive targeting operation, uncertainty and high task load are the rule, not the exception. When the loop between sensor and shooter is short, the pressure on the crew in GCS can be extremely high, giving rise to psychological phenomena that are unique to UAV operations. Current-day warfare, with highly unpredictable targets, is clearly moving towards shorter sensor-to-shooter loops.

In the remainder of this section we will further discuss team training, specifically for UAV operators. We will also present the concept of embedded training, and provide a sketch of how such a system could be beneficial for operator team training.

4.5.2.2 What is Embedded Training?

For the current purposes we define Embedded Training (ET) as a form of training in which simulated ‘entities’ such as threats and targets are fed into the various avionics systems of an actual working UAV-system. This allows training against virtual threats and with virtual targets. ET enables UAV crew in the Ground Control Station (GCS) to use the system in a situation where it was designed for, while this situation is not available in every day life. Thus providing capabilities to train UAV crew more effectively using the real equipment in combination with a partly simulated environment.

An ET mission potentially provides the context of a real UAV mission, but without the need for the actual presence of mission-critical entities, such as targets to be observed, ground threats, airborne threats or friendly forces. One proposed ET architecture presupposes an airborne UAV, capable of ET, which maneuvers through a reserved airspace sector. The interaction with aforementioned entities is simulated with on-board equipment. Another proposed ET architecture does not require an airborne UAV, but only a functional GCS, that is capable of ET. Multiple, fundamentally different ET architectures are possible, and the aforementioned architectures are two examples. Although the circumstances and tensions of a real mission will probably never be accurately simulated, ET can come closer than traditional forms of training by representing assets in the real environment. A UAV embedded training is however clearly different from a manned fighter ET: UAV operators are physically located in a GCS. While the air vehicle performs its ‘dull, dirty and dangerous’ tasks in the war zone the operators are physically safe. Why ET in UAV then? A number of arguments can be given, including:

- ET provides increased training effectiveness through added immersion, highly effective training scenarios and team involvement.
- ET potentially enables ‘complete’ team training, including training of personnel involved in launch and recovery, CAOC personnel, operators of manned platforms, logistics, maintenance, and, last but not least, data analysts.
- ET would also lead to efficient use of costly flight time. Independent of the availability of other players, operators can go through complex scenarios with simulated entities in each flight. In another application, mission rehearsal could take place while loitering or en-route to operational area.

Previous research with fighter aircraft has demonstrated that ET is a technologically and operationally viable concept [2,3,4]. Reus and Stokkel [5] and Roessingh et al. [6] investigated specific PVI-issues associated with ET. Now R&D needs to focus on ET for UAV crews. If the operational use and benefits for UAV operations can be demonstrated, it is worthwhile to require these capabilities for the next generation of UAVs. In the following sections the reader is given a brief account of some of the principles underlying ET.

4.5.2.3 Why Combine Real and Simulated Systems?

The ET system feeds additional entities, such as targets and threats, into the mission system of the UAV system. These data are treated in the GCS as if being real data and will be displayed as such. The crew in GCS (supposedly consisting of UAV operator, payload operator, and a mission commander) needs to interact with these entities based on their predefined roles. In the preceding section we argued that ET is a form of high fidelity mission training. This is a strong argument for serious consideration of implementation. However, some more direct and quantifiable advantages can be argued for as well.

- In live training without ET, e.g., on a training range, physical entities are needed that act as targets, threats or friendly forces. These physical entities are costly to implement and obviously only have a

restricted training value for the personnel involved operating these entities. It is clear that with budgetary constraints on live training hours, ET will be very cost effective.

- Depending on the chosen architecture ET does not need airspace or only relatively small volume of airspace. In many of today's and future missions, UAVs are equipped with long-range sensors, which means that detection of targets, identification, electronic warfare, and possibly weapon delivery, may all take place at relatively long distances between the players. Airspace where such skills as electronic warfare can be trained in live training is very limited, particularly in Europe. Since ET allows any geometry of threats, targets and other players to be simulated, only a very restricted volume of airspace is needed. ET allows virtual entities to fly outside the designated area as long as the UAV remains within the designated airspace.
- Because the actual system dynamics are present in ET, this form of training is to be preferred over legacy simulation, particularly when the crew has to combine various skills and knowledge in an integrated manner, such as co-ordination and co-operation, tactics, perceptual skills, control skills and attention management.
- UAVs may operate under control of other platforms, such as Airborne Early Warning platform (AWACS). During training however these systems are not always available. ET is able to provide the AWACS control capabilities in case these systems are not available. Thereby ET trains the crew the necessary skills on a day to day basis.
- Certain capabilities of UAVs will not be used during live training due to security or safety reasons. Specifically Low Observerability (LO) characteristics are expected to not being used to the full extent during training because of security aspects. ET allows training with the LO characteristics with virtual systems. Another aspect is training with lasers, e.g., for target designation. Lasers can only be used in a specific environment due to safety reasons. ET allows the deployment of virtual lasers. This increases the crew's readiness for real missions.

4.5.2.4 The Architectural Concept of Embedded Training

Basic Architecture

An ET system, implemented in a UAV system, consists of three main simulation modules (Figure 4-7).

- First, the simulation management module performs many functions, such as starting and stopping training exercises and taking care that all players participating in the exercise have synchronised information.
- Second, the UAV simulation module stimulates the on-board sensors and simulates the own weapons and electronic warfare systems.
- Third, the virtual world simulation simulates the virtual entities in the exercise. The virtual world simulation also comprises models for the terrain over which the exercise takes place and atmospheric conditions.

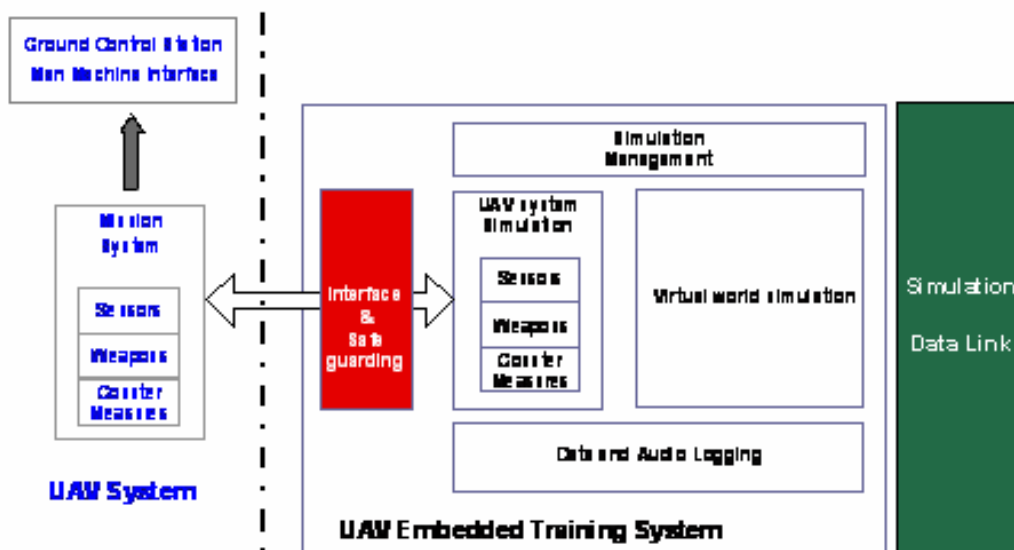


Figure 4-7: Basic Architecture of an Embedded Training System.

To make the crew believe that they are in a real mission, the three simulation modules maintain an intensive two-way communication with the UAV's standard mission system. The mission system consists of modules that handle sensor data, weapon data, and electronic warfare data. Every time the crew gives an input to one of the systems in the GCS, the simulation needs to be updated and, as a result, new simulation data need to be fed into the mission system. To ensure a safe exercise a specific safety layer that safeguards the UAV mission system must be developed.

The above described basic architecture is sufficient for the training of engagements in which one ET equipped UAV system is involved and all other entities are virtual. However, in more complex and realistic exercises, that is, beyond the single UAV operations, an airborne datalink between ET carrying UAVs and an air-to-ground datalink between UAVs and ground-based entities are needed to ensure that all players have matching sensor information.

A scenario for the exercise needs to be prepared in advance on a dedicated GCS. After sufficient verification of the scenario, its digital representation can be loaded in the ET carrying UAV, either by physically inserting a credit-card-size memory card into the system or by datalink. The GCS can also be used for debriefing purposes.

4.5.2.4.1 Simulation Management

During the exercise, the simulation management module must control all simulations as well as the overall course of the exercise. In addition, this module manages the recording of the exercise and performance measurement. Since complex exercises have many performance aspects, proper assessment of crew performance is a major challenge to UAV crew training in general and specifically to ET. The performance aspects include the use of sensors and countermeasures, selection of tactics, following the mission routes and selection/assignment of targets. Intelligent methods are needed to keep track and analyse the crew's activities, to categorise crew error and to determine mission success. Transfer-of-training will increase when such performance measures can be singled out, both during the exercise and in debriefing.

4.5.2.4.2 UAV System Simulation

In the UAV system simulation a complete dynamic model of the UAV system is included. UAV system simulation includes models for the electronic warfare system and for on-board weapons (when present). An important part of the UAV system simulation is a realistic assessment of mission effectiveness. System displays in the GCS, such as the radar, the radar warning receiver and target identification means must interact as if real targets are present. These provisions make it possible that missions can be fully exercised.

4.5.2.4.3 Virtual World Simulation

The virtual world includes the virtual entities, their electronic signatures, weapons and dynamic behavior, involving strategies, tactics, maneuvers and counter measures. Moreover, the behavior of the virtual entities has to be in exact accordance with their individual role (ground-based or airborne, friend or foe, etc.).

4.5.2.5 Safeguarding for Embedded Training

When an air vehicle is being flown in UAV operator training, safety is an important issue. Safety issues are related to the air vehicle itself, and to the interaction between the air vehicle and its environment. Systems and working procedures help the operators to guarantee a sufficient safety level. As an example, presentation of air traffic in relation to the air vehicle allows the operators to avoid collisions with manned or uninhabited aircraft. The situation in an embedded training scenario is somewhat more complex, since parts of the environment are real, while other parts are simulated. For example, an operator may concurrently see real and virtual entities on the same tactical display.

We clearly do not want to compromise safety by introducing virtual entities in a scenario; unsafe situations in response to virtual entities are simply unacceptable. Thus, measures have to be taken to avoid damage to the air vehicle itself, for example caused by collisions with air traffic or terrain. Also, risks to third parties, such as manned military aircraft, other UAVs, civil air traffic, and population on the ground, should be minimised. Therefore, just like in a fighter aircraft ET system, safeguarding is an important issue in the design of a UAV embedded trainer. Also, a similar approach to safeguarding can be foreseen. The starting point is that all operators are at all time aware that a simulation is running, so continuous presentation of the simulation status is a firm requirement. Further, the simulation should explicitly indicate when it starts and stops. An aural annunciation in the GCS is a proper method, since it is independent of the individual point-of-gaze of the operator team.

Since displays can contain both real and virtual information at the same time, operators should always be aware which information is real and which is virtual. This helps them to make the appropriate trade-offs and decisions during the training scenario. It is clearly not desirable to perform a potentially unsafe manoeuvre or action in response to a virtual entity, while this may be totally justified in an operational situation. A potential implementation for symbols on a display is to give the virtual entities a dedicated supplementary tag. In the fighter embedded training system that was developed at NLR, this is accomplished by attaching a small “v” to each virtual symbol on all displays where they can appear. Naturally such information should be designed carefully in order to guarantee positive transfer of training. Another effective strategy in the design of displays is to give symbols related to real entities a higher priority. This way, symbols related to virtual entities do never obscure those related to real entities.

More advanced means are also possible. Automatic monitoring of the air vehicle and its interaction with the real environment can prevent unsafe situations. This can be accomplished by the continuous evaluation of a number of safety rules by the simulation itself. The simulation immediately stops when one of the rules is

violated, that is, when it detects an unsafe situation. Naturally this should be properly announced to the operators. As an example, the system can monitor that the air vehicle remains in a temporary reserved airspace during the training. It could also automatically detect potential collisions with real entities or real terrain.

4.5.2.6 Choosing an Embedded Training Architecture

Various architectures are possible when implementing a UAV embedded training system, but two distinct groups can be identified. In the first group an air vehicle is not required, only a GCS is needed for the exercises. In this case ET is built into the GCS and directly communicates with the GCS systems. The second group is fundamentally different and involves a flying air vehicle during the exercises. ET then communicates with the on-board systems and (via the datalink) with the GCS. The simulation itself can be in the air vehicle or in the GCS, while it is also possible to implement a part of the simulation on board and a part in the GCS. Naturally this is related to the decision to involve a flying air vehicle in the training.

This is not the place to promote a specific architecture, but some arguments will definitely play a role in the selection.

- Training effectiveness. Nowadays simulation standards are high, but the psychological factors involved in operating a high valued asset with all potential safety consequences, can never be reproduced in a simulator.
- Cost of flight hours. These costs are not only due to fuel, but also to the number of personnel involved in the training, complicated logistics, and need for air vehicle maintenance. Nowadays, optimal use of the limited number of flight hours is an important concern.
- External safety issues are important, particularly during training operations, when the air vehicle is over populated areas and when sharing airspace with other vehicles. Safety of the air vehicle is important too. The costs associated with the loss of an air vehicle and collateral damage on the ground can be enormous, also in the ‘public eye’. Also, the consequences of a collision with other vehicles can be dramatic.
- Security. Flying an air vehicle implies using a datalink and exposing the UAV system and tactics to interested parties.

4.5.2.7 Team Training to be Addressed with Embedded Training

4.5.2.7.1 Teamwork

We define teamwork as the seamless integration of specific skills, knowledge and attitudes (SKAs) that allow team members to adapt and optimize their performance. Team characteristics that distinguish teams from small groups include the following [7,8,9,10]:

- 1) Multiple sources of information.
- 2) Task interdependencies.
- 3) Coordination among members.
- 4) Common and valued goals.
- 5) Specialised member roles and responsibilities.
- 6) Task-relevant knowledge.

- 7) Intensive communication.
- 8) Adaptive strategies to help respond to change.

4.5.2.7.2 *Team Skills*

Some team skills are frequently mentioned in the literature. For the purpose of UAV operations we have selected four of these skills. The first one is ‘team monitoring’, which means mutual performance monitoring by team members, but also mutual workload monitoring and predicting each others’ behavior [11,12]. A second frequently mentioned team skill is ‘exhibiting flexibility’ which includes adapting to novel and unpredictable situations [13]. A third team skills is exhibiting team leadership or followership (depending on the situation), which means motivating team members, exhibiting team initiative, exhibiting assertiveness and providing supporting behaviors [14,15,16,10]. Fourth, we mention ‘team coordination’, which is the skill of giving suggestions or criticisms, but also accepting suggestions or criticism, including performing of self-correction [17,18]. Less frequently mentioned skills include response coordination, coordination activities, resource distribution, timing, interpersonal coordination, team decision-making, shared situation awareness [19,20,14].

4.5.2.7.3 *Team Knowledge*

Knowledge is difficult to define, but generally the following building blocks are recognised:

- 1) Declarative knowledge (facts and concepts);
- 2) Procedural knowledge: procedures and strategies; and
- 3) Conditional knowledge: principles and conditions.

Examples of teamwork knowledge in these different categories are

- 1) Understanding one’s own function in the team;
- 2) Knowledge of communication strategies such as ways to give and receive feedback and constructive criticism; and
- 3) The principles and conditions for creating and retaining a good teamwork atmosphere.

Teamwork knowledge is typically acquired during education, dedicated Team Resource Management (TRM) courses and similar specialised initiatives. However, teamwork knowledge also builds up through operational experience, which provides insight in the operations, procedures and processes and the knowledge to keep track of the situation and to ‘read the game’.

Obviously, there is much more to say about the knowledge underlying successful teamwork, and how this knowledge is acquired. Literature on the topic is abundant. However, there is an overlap between the knowledge underlying team skills and the skills of the team. Knowledge that has been effectively acquired will enable the development of skills through practice. For example, knowledge about strategies on how to communicate effectively may enable the skills to communicate effectively and knowledge of the effect of stress on teamwork, allows the team to recognise the symptoms and develop teamwork skills for coping with stress.

4.5.2.7.4 *Team Attitudes*

Team attitudes are defined as an internal state that influences a team member’s choices or decisions to act in a particular way [21]. Attitudes toward teamwork can have a significant effect on how teamwork scales are

actually put into practice [22]. Positive attitudes toward teamwork and an attraction to being part of a team ('collective orientation') have been found to enhance team processes and team performance. Some important attitudes found in the general literature are team spirit, team morale, belief in the importance of teamwork, team cohesion, shared vision, mutual trust, collective orientation [19,23,24,25,26,9,16,10].

4.5.2.7.5 Types of Team Training

Although no specialized investigations have been made with respect to the types of UAV team training that could be addressed with ET, knowledge from related domains suggests that ET could be applied for:

- Qualification training (including training for the conversion to the specific UAV);
- Day-to-day routine training at the operational unit;
- Team Resource Management training; and
- Emergency Management Command and Control (EMC2) training.

Use of ET would promote unity in operational procedures and doctrines, and be of use to train effective communication techniques, learn to overcome barriers to effective communication and awareness of strengths and weaknesses in personal communication skills. Training scenarios could, inter alia, be based on actual battlefield incidents involving factors related to teamwork (e.g., during migration of control). Such incidents with UAVs in which teamwork was a (contributory) factor are known and should be reported carefully and in detail.

4.5.2.8 Conclusions

The effectiveness of the core team operating a UAV system depends to a large extent on the teamwork of the team-members. During the flight over the battlefield the team has to deal with unplanned situations. In these situations, inefficient and ineffective team co-ordination can severely impair mission success and safety. For training of the core team in or near the GCS (mission commander, air vehicle operator, payload operator, data analysts) Embedded Training provides increased training effectiveness when compared to live training or legacy simulation training. ET would also lead to more efficient use of costly UAV flight time, when compared to live training. A number of additional advantages have been sketched, the extent of which depending on the specific architecture of the ET system. The two basic architectures are (1) ET technology concentrated on board of the air vehicle, the latter being in flight during ET, and (2) ET technology only in the GCS, with no role for the air vehicle during ET. The first architecture is the most innovative and technological challenging; particularly to safeguard the air vehicle against mishaps induced by the simulation. Teamwork has been analyzed with respect to teams skills, team knowledge and team attitudes. The tentative conclusion of this paragraph is that these skills can be addressed by the embedded training concept, particularly when applied in the qualification and conversion training, routine operational training, and focused team training such as team resource management training.

4.5.2.9 References

- [1] Cohen, M.S., Freeman, J.T. and Wolf, S.W. (1996). Metarecognition in time-stressed decision making: Recognizing, critiquing, and correction. *Human Factors*, 38(2), 206-219.
- [2] NLR (2002). Weapon System Simulation in Flight (WASIF) – WASIF System Design Final Report. report NLR-CR-2002-355. National Aerospace Laboratory NLR, Amsterdam, The Netherlands.

- [3] AerMacchi (2003). In-flight demonstration of Embedded Simulation for training purposes on-board fighter aircraft. WASIF ABS Flight Test Report. Document ID: EUC-RTP11.12-TRP-7400-001-AeM. AerMacchi SpA, Italy.
- [4] ECATS (2004). Consolidated Trip Report – Dutch Embedded Training Demo, Leeuwarden Airbase, 5-9 April, 2004. Joint Strike Fighter Program Office, Washington, US.
- [5] Reus, A. de and Stokkel, F. (1997) Man-Machine Interface Aspects. In: EUCLID RTP 11.7 Training Simulation Combining Real and Simulated Systems (WASIF). Document ID. EUC/RTP11.7/NLR/TN230/I2.
- [6] Roessingh, J.J.M., van Sijll, M. and Johnson, S.P. (2003). Embedded Training – An explorative study providing requirements for the display of virtual targets on a Helmet Mounted Display in simulated air-to-air engagements within visual range. NLR Technical Publication – NLR-TP-2003-262, Amsterdam, The Netherlands.
- [7] Dwyer, D.J. (1984). Team research and team training: a state of the art review. In: F.A. Muckler (Ed.), Human Factors Review. Santa Monica, CA, US: Human Factors and Ergonomics Society.
- [8] Modrick, J.A. (1986). Team performance and training. In: J. Zeidner (Ed.), Human Productivity Enhancement: Training and Human Factors in Systems Design, Vol. 1. New York, US: Praeger.
- [9] Morgan, B.B. Jr., Glickman, A.S., Woodward, E.A., Blaiwes, A.S. and Salas, E. (1986). Measurement of team behaviours in a navy environment. NTSC technical report TR-86-014, Orlando, FL, US: NTSC.
- [10] Salas, E. and Cannon-Bowers, J.A. (2000). The anatomy of team training. In: L. Tobias and D. Fletcher (Eds), Handbook on research in training. New York, US: MacMillan.
- [11] Hackman, J.R. (1990). Groups that work (and those that don't): Creating conditions for effective teamwork. San Francisco, US: Jossey-Bass.
- [12] Volpe, C.E., Cannon-Bowers, J.A., Salas, E. and Spector, P. (1996). The impact of cross training on team functioning. Human Factors, 38, 87-100.
- [13] Prince, C. and Salas, E. (1993). Training and research for teamwork in the military aircrew. In: E.L. Wiener, B.G. Kanki and R.L. Helmreich (Eds), Cockpit resource management, 337-366. Orlando, FL, US: Academic Press.
- [14] Smith-Jentsch, K.A., Zeisig, R.L., Acton, B. and McPherson, J.A. (1998). Team dimensional training: A strategy for guided team self-correction. In: J.A. Cannon-Bowers and E. Salas (Eds), Making decisions under stress: Implications for individual and team training, 271-297 Washington, DC, US: APA Press.
- [15] Smith-Jentsch, K.A., Salas, E. and Baker, D. (1996). Training team performance-related assertiveness. Personnel Psychology, 49, 909-936.
- [16] Cannon-Bowers, J.A., Tannenbaum, S.I., Salas, E. and Volpe, C.E. (1995). Defining team competencies and establishing team training requirements. In: R. Guzzo and E. Salas (Eds), Team effectiveness and decision-making in organizations, 333-380. San Francisco, CA, US: Jossey Bass.

- [17] McIntyre, R.M. and Salas, E. (1995). Measuring and managing for team performance: Emerging principles from complex environments. In: R. Guzzo and E. Salas (Eds), Team effectiveness and decision-making in organizations, 149-203. San Francisco, CA, US: Jossey-Bass.
- [18] Curry, M. (2005). NASA – Past projects – Helios prototype. Retrieved July 30, 2005, from <http://www.nasa.gov/centers/Dryden/history/pastprojects/Erast/helios.html>
- [19] Nieva, V.F., Fleishman, E.A. and Reick, A. (1978). Team Dimensions: Their Identity, Their Measurement, and Their Relationships. D.C.: Response Analysis Corporation.
- [20] Kleinman, D.L. and Serfaty, D. (1989). Team Performance assessment in distributed decision-making. Proceedings of the Symposium on Interactive Networked Simulation for Training, 22-27, Orlando, FL, US.
- [21] Cannon-Bowers, J.A., Tannenbaum, S.I., Salas, E. and Volpe, C.E. (1995). Defining team competencies and establishing team training requirements. In: R. Guzzo and E. Salas (Eds), Team effectiveness and decision-making in organizations, 333-380. San Francisco, CA, US: Jossey Bass.
- [22] Smith, E.A. (2002). Effects Based Operations: Applying Network Centric Warfare in Peace, Crisis, and War. Washington, DC: CCRP.
- [23] Driskell, J.E. and Salas, E. (1992). Collective behavior and team performance. Human Factors, 34, 277-288.
- [24] Mullen, B. and Copper, C. (1994). The relation between group cohesiveness and performance: an integration. Psychological Bulletin, 115, 210-217.
- [25] Gregorich, S.E., Helmreich, R.L. and Wilhelm, J.A. (1990). The structure of cockpit management attitudes, Journal of Applied Psychology, 75, 782-690.
- [26] Ruffell-Smith, H.P. (1979). A simulator study of the interaction of pilot workload with errors. NASA Technical Report No. TM-78482. Moffett Field, CA, US: National Aeronautics and Space Administration-Ames Research Center.



Chapter 5 – ARTIFICIAL COGNITION AND CO-OPERATIVE AUTOMATION

Chapter Lead: A. Schulte

Contributors: M. Chamberlin, J. Edwards, A. Schulte, R. Taylor, M. Waters

Within the scope of this report on “Uninhabited Military Vehicles: Human Factors in Augmenting the Force”, the present chapter is dedicated to the involvement of the human factor with the specific aspect of the integration of artificial cognition in the process of vehicle guidance and supervision. In particular, the idea of co-operative control, i.e., the co-operation between the human operator and automation, will be addressed. Hence, human-automation integration can be viewed from two different standpoints, each of which facilitating the other. On the one hand, the human has to be considered as the user of technology, being the operator in a somehow automated work environment, responsible for the pursuit of the ongoing processes and provided with more or less authority. On the other hand, the consideration of human performance in work processes suggests unique approaches to automation and decision systems design for the future. These approaches reveal the potential of human-like behaving machines (in the sense of rational behaviour) in certain given task domains, even being able to co-operate, as well as the potential of a human-centred automation, promising significant performance advances, once introduced into a work place.

The following sections will provide a discussion of the human involvement aspects as named above from a conceptual point of view, to begin with. Further down, application examples taken from current research will be illustrated, covering different application areas as well as different perspectives in terms of human involvement.

Firstly, the scope of the discussion will be delimited. Bearing in mind that the following considerations shall have the potential to be applicable in the air, land, sea, space and underwater domain likewise, it is useful to restrict oneself to some more specific field, in particular in closely application-related research. So, the aviation domain, specifically flight guidance and mission management of military aircraft, conventionally manned and unmanned likewise, will mark the vantage point of the following discussion. The motivation of this selection against the background of the consideration of human cognition and decision-making will be explained.

The next section will provide a statement on the current, i.e., the solution of conventional automation being strongly influenced by the paradigm of supervisory control. A framework for the modelling of the work process and related control levels will be briefly discussed. Domain specific technology approaches will be roughly structured, again considering flight guidance as an example.

Problems arising from conventional automation approaches will be discussed in the third section. Perspectives of future automation and required extensions will be introduced. At this stage the notion of an Artificial Cognitive Unit (ACU) as part of a work system will be introduced. The required capabilities of such a machine being a team mate will be estimated.

The outcome of the consideration of these required advances in automation is to concentrate on the treatment of human and machine cognition as an inter-disciplinary approach based upon cognitive psychology and artificial intelligence as branch of information technology. This will be the objective of the fourth section. As an interim result the theory of the Cognitive Process will be introduced in this section.

Section 5.5 briefly gives some information on realisation aspects of the Cognitive Process, being the underlying theory itself. Creating a cognitive system according to this theory requires the implementation of a systems engineering framework.

Section 5.6 will broaden the view from which the issue of artificial cognition and co-operative automation has been looked at so far, by opening up the podium for different, but related perspectives covering the fields of Artificial Intelligence methods evaluation, knowledge engineering and an application in the underwater vehicle guidance domain.

5.1 SCOPE

As already mentioned in the introduction the rather broad scope of possible air, land, sea, space and underwater applications needs to be narrowed somehow, taking advantage of digging deeper into the specific problems of one particular domain, finally providing beneficial insight ready to be adopted by other application areas. In anticipation of the main scope of this chapter the airborne application is the choice. It is a fact, that conventional automation, a term which will be defined further down, can be regarded as very advanced in this domain. Modern electronic fly-by-wire systems enable an almost fully automatic performance of an entire mission, as daily demonstrated in thousands of civil airliner flights. Generating and pursuing a four-dimensional flight trajectory is not a real technological challenge any more, but provides a very sustainable platform for further considerations to be endeavoured here. Especially the higher levels of cognitive performance involving problem-solving, and decision-making are still mostly attributed to the human operator acting as supervisor of a technical process.

In contrast to this, the situation, e.g., in ground based application is somehow inverted. Autonomous driving is still a complicated issue (as observed during the recent DARPA grand challenge), i.e., the automation of the lower guidance levels including the recognition of the nearest environment and the resulting stabilisation and tracking tasks are not at all fully available today. In fact, current research is focused here. On the other hand a car navigation system supporting on the supervisory control level is almost present in every upper middle-sized class car. Virtually every tactical decision emerging in every day's driving will already be covered. Currently up-coming so-called driver assistant systems, which in most cases correspond with the functions of conventional aircraft automation, call for action in terms of central co-ordination of their supervision for efficient operation.

Again, the scope of this chapter shall be the automation of tasks on that supervisory level. As a result, systems shall be enabled towards autonomous task accomplishment. This issue of autonomy will be discussed in some more depth. Another very important issue will be the consideration of human-machine teaming and co-operation. The following sub-sections outline a typical aerial warfare mission to serve as a benchmark, providing a most interesting challenge for the concepts to be presented here – i.e., the relevant scenario shall be described mostly on a symbolic level, minimising the involvement of the processing of signals. The focus shall be more upon the logical relations between the objects, rather than upon their physical properties.

5.1.1 Typical Scenario from the Military Aviation Domain

The benchmark mission shall be taken from the aerial warfare domain. Figure 5-1 depicts an overview of the scenario and the relevant objects of a multi-ship air-to-ground attack mission. The own forces consist of the airborne component covering different rolls such as reconnaissance (RECCE), suppression of enemy air defence (SEAD) and attack. Furthermore, a command and control (C2) component might be involved, possibly airborne, typically ground-based.

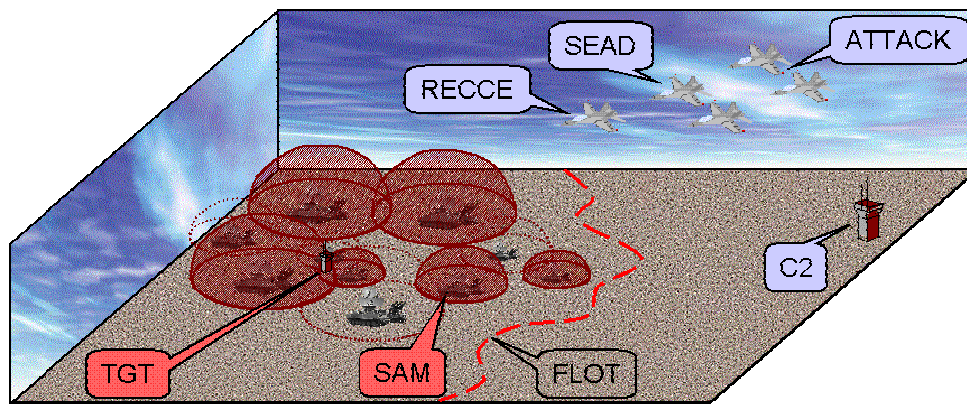


Figure 5-1: Scenario for Multi-Ship Air-to-Ground Attack Mission.

The hostile forces consist mainly of two components, i.e., a military target, fixed or moving and a ground-based air-defence system represented by surface-to-air missile (SAM) sites, which can be switched on and off, and which are to some extent known during the mission preparation phase both of which are separated from the safe territory by the forward line of own troops (FLOT). The mission order requires the attack component to destroy the hostile target. To achieve this, SAM-sites temporarily have to be suppressed or destroyed.

Although massively simplified with respect to asymmetric warfare scenarios currently discussed by NATO, this scenario bears a great variety of challenges in terms of integrated mission systems and automation.

5.1.2 Forces Structure

The own airborne forces will be a whatsoever mix of manned and un-manned platforms, to begin with. The scenario envisions a set of platforms, which have no static role or task allocation (A static role allocation in this context could be “Reconnaissance A/C or UAV searching, combat A/C or UAV shooting”). These platforms form a heterogeneous team, which means that the entities may differ from each other with respect to resources and capabilities, such as sensors, actuators, weapons, and information processing. This heterogeneous team structure does not prohibit homogeneous sub-structures, i.e., that some team members have equal or partially overlapping resources and capabilities. The envisioned scenario requires co-operation capabilities of the participating forces, because otherwise the mission cannot be accomplished [1].

A more generalised standpoint is shown in Figure 5-2. Starting from a classical situation, where single or multiple manned vehicles perform the mission. The critical questions arise when un-inhabited aerial vehicles (UAV) enter the scene. It has to be decided whether the UAVs will substitute or supplement the conventional manned platforms [2]. Obviously in some cases substitution will be an isolated solution, especially thinking of the so-called DDD-missions (dull-dirty-dangerous) – but generally, we certainly have to face the technological challenges of the solution of supplementation of forces, including the issues of manned-unmanned teaming, co-operation and supervision.

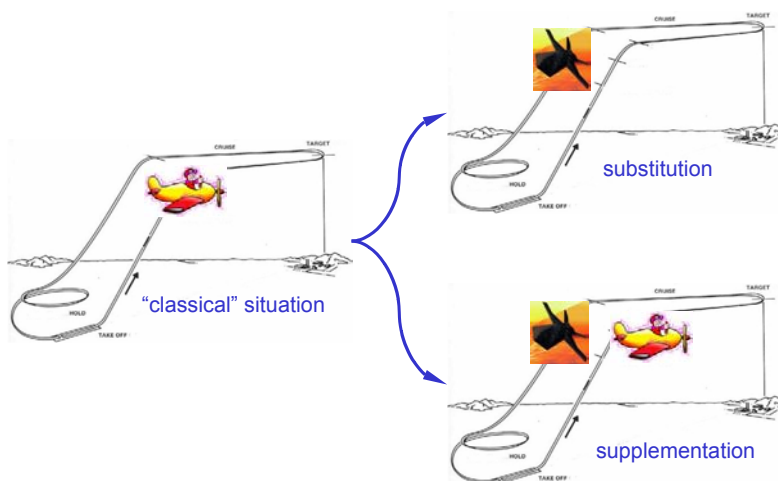


Figure 5-2: Possible Characteristics in Future UAV Deployment – Substitution and/or Supplementation.

5.1.3 References

- [1] Ertl, C. and Schulte, A. (2004, September). System Design Concepts for Co-operative and Autonomous Mission Accomplishment of UAVs. In: Deutscher Luft- und Raumfahrtkongress. Dresden, GE. 20-23.
- [2] Schulte, A. (2003, 10th – 13th June). Systems Engineering Framework Defining Required Functions of Un-inhabited Intelligent Vehicle Guidance. In: NATO RTO. Human Factors and Medicine Panel. Task Group HFM-078 on Unmanned Military Vehicles: Human Factors in Augmenting the Force. Leiden, NL.

5.2 THE WORK PROCESS AND CONVENTIONAL AUTOMATION'S SOLUTION

The last section gave a brief outline of the challenge for future mission systems. Needless to say, this type of mission can already be performed today, in one or the other way. The scope of this report of course is the augmented exploitation of presently unrevealed abilities in manned-unmanned teaming. To do so, the first step here shall be characterisation of current automation, i.e., the solution of conventional automation. For the later discrimination between automatic and autonomous performance the consideration of the work system will be helpful.

5.2.1 The Work System

The work system as a general ergonomics concept [1] has been utilised in the application domain of human-machine co-operation in aircraft flight guidance by [2]. Figure 5-3 shows an adaptation of the concept incorporating some application specific imagery for the purpose of intuitive understanding.

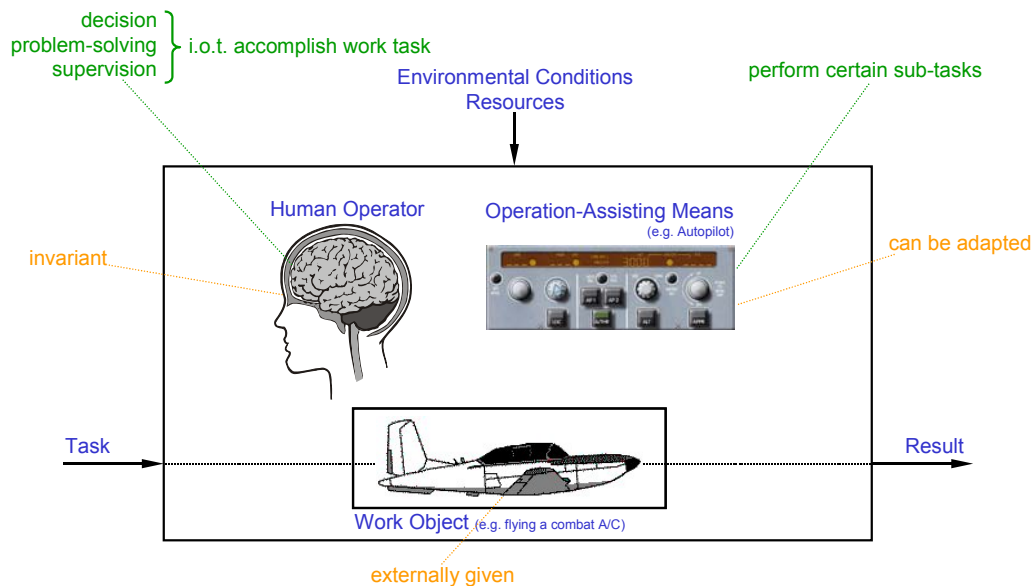


Figure 5-3: Concept of Work System.

The work system consists of three major elements, i.e., the operator, the work object and operation-assisting means, as characterised in some more detail here:

- Operator:** In the traditional view of a work system the operator is usually a human operator, being in charge of performing a certain given task, such as accomplishing a combat mission, as according to the chosen application. The human operator is the high end decision element of the work system. He determines and supervises within the work system what will happen with the work object. This can be done by working on any required performance level, including manual control. In highly automated work systems, as we are talking of, the human performance is usually focused on supervisory control, including decision-making and problem-solving in order to comply with the work task. As according to the common view of ergonomics, the abilities of the skilled and trained human operator in terms of information processing performance can be seen as pretty much invariant in an average.
- Work Object:** The notion of the work object is not necessarily restricted to the physical nature of whatever machine, but also comprises dynamical processes, i.e., the progression of the situation over time. In the chosen application domain, the work object may be the mission of a combat aircraft or UAV.
- Operation-Assisting Means:** The concept of the operation-assisting means can be seen as a container for whatever tools or automation of the work place is available, being computerised pieces of technology in many cases. In our application domain an auto-flight/autopilot system including the human-machine control interface (i.e., FCU – flight control unit), or even the aircraft itself as a means of transport may serve as typical examples. Common to the nature of various operation-assisting means is the fact that they only perform certain sub-tasks (e.g., pursuing a given flight trajectory, holding a defined heading). Such a sub-task does not form a work system itself, obviously being only a part of another higher level work task. In today's common ergonomic design, the operation-assisting means are typically subjected to the endeavours of adaptation and optimisation in order to meet overall system requirements and further improvements.

These elements will be combined to the work system set up in order to achieve a certain work result on the basis of a given high level work task. The accomplishment of a military flight mission may give a good idea of what is meant here. Finally, environmental conditions and external resources, such as information, material, or energy will affect the ongoing work process.

The concept of the work system seems very suitable for the consideration of problems to be discussed in the further pursuit of this elaboration. The reason for this is the fact that the work process is constituted by the work task and the desired result, no matter its technical or organisational structure. However, exactly this technical or organisational structure might as well be easily modelled and analysed by the framework given by the work system. Yet, the notion of the work system at this stage gives no hints of modelling the mechanisms of human performance.

In order to do so, a very common model of human control performance shall be mentioned here, where a distinction is drawn between manual and supervisory control. This issue has been elaborately investigated by Thomas B. Sheridan at MIT (e.g., [3]) with a more recent focus on tele-operation [4], where obviously supervisory control predominates due to the remoteness of the work object.

Figure 5-4, which is adapted from [3], shows an automated human-machine system with the human operator in manual control mode on the left hand side. In this situation the human operator is busy in feedback control of the inner loops of the underlying process. Typical for the manual control mode are any kind of tracking tasks such as lateral car steering or attitude control of an aircraft. Automation is mainly responsible for the transformation and transmission of the required signals. On the right hand side of Figure 5-4, the automation takes over the role of automatically closing higher bandwidth control loops as to the dynamic process. In this case the human operator's role is shifted towards the supervisory control mode, where the tasks of monitoring and setting demand values for the automated control process are relevant.

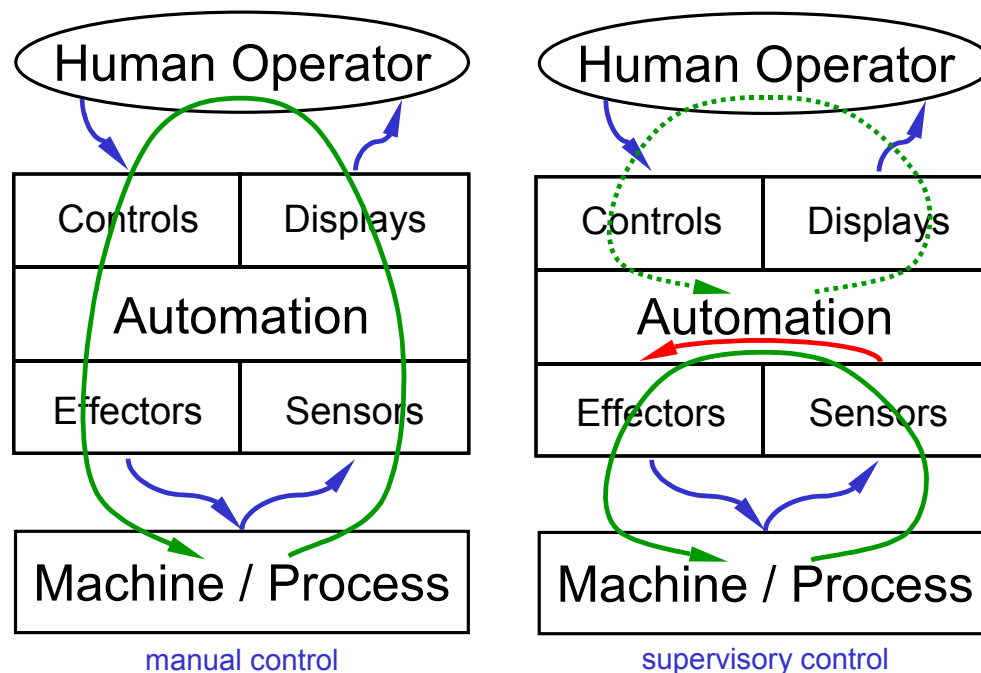


Figure 5-4: Manual and Supervisory Control.

In order to approach another definition of supervisory control [5] states:

“When a process is semi-automated or responds very slowly, it is not necessary for a human to devote full attention to that process, [...] In situations where [...] the process] is automatically controlled, we can view the human as a supervisor whose role includes monitoring the process [...], adjusting the reference points [...], and intervening in the case of failures and emergencies.” [Rouse, 1980]

Many real-world applications in fact will require human-machine interaction as a mixture of manual and supervisory control as a function of the level of automation selected. The human operator will permanently toggle between the two control modes, allocating varying amounts of attention to one or the other task.

In order to prepare a common ground for the further discussion of models of human performance, this sub-section shall be closing with the introduction of a human model of manual and supervisory control advocated by [5]. The adapted model is set in the aviation domain context and depicted in Figure 5-5.

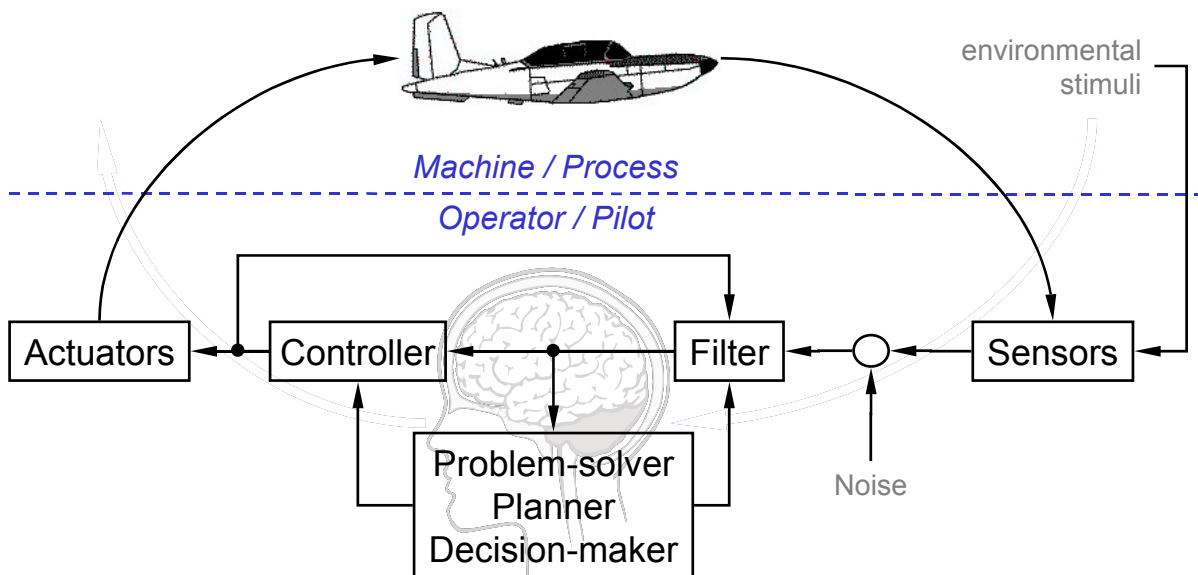


Figure 5-5: Model of Human Manual and Supervisory Control.

In Figure 5-5 the direct functional chain of sensing process and environmental parameters, filtering the information, applying control laws, and finally acting on the process represents all that is involved in the execution of manual control. On a supervisory control level gathered and filtered information will be fed into a functional block representing problem-solving, planning and decision-making. This block in turn will determine the demand values for the controller. Furthermore it allows the selection of the control mode and the adaptation of the control laws according to the current task. Finally, the decision-maker will adjust the filter in terms of selective allocation of resources such as attention (e.g., [6]).

5.2.2 The Hierarchy of a Conventional Guidance and Control System

In the previous sub-section the focus was drawn to the human operator's aspects of the work system for the first time. This sub-section shall concentrate more upon the operation-assisting means, i.e., the automation.

Obviously, the characteristic of the operation-assisting means is dependent on the application domain to a great extent. This is the point where we get back to the aviation domain as an example.

Figure 5-6 shows the major building blocks of a common hierarchical architecture of a state-of-the-art flight guidance and control system with several nested loops (adapted from [7]). Besides the many closed control loops on the machine side, one loop is closed involving the human operator, i.e., the pilot. Obviously this architecture puts the pilot into a versatile situation of supervisory control, using all these fancy machine functions. Direct intervention in manual control style is likewise possible on the lowest (i.e., most right in Figure 5-6) interaction level. It should be mentioned that Sheridan's notion of manual control, being unaffected by automated control loops, is to some extent impaired by the current technology of control-configured vehicles ("fly-by-wire"), where the lowest available human interaction level already implicates automatic control. Nevertheless, the human interaction with such a system might be denoted as manual control on that particular interaction level.

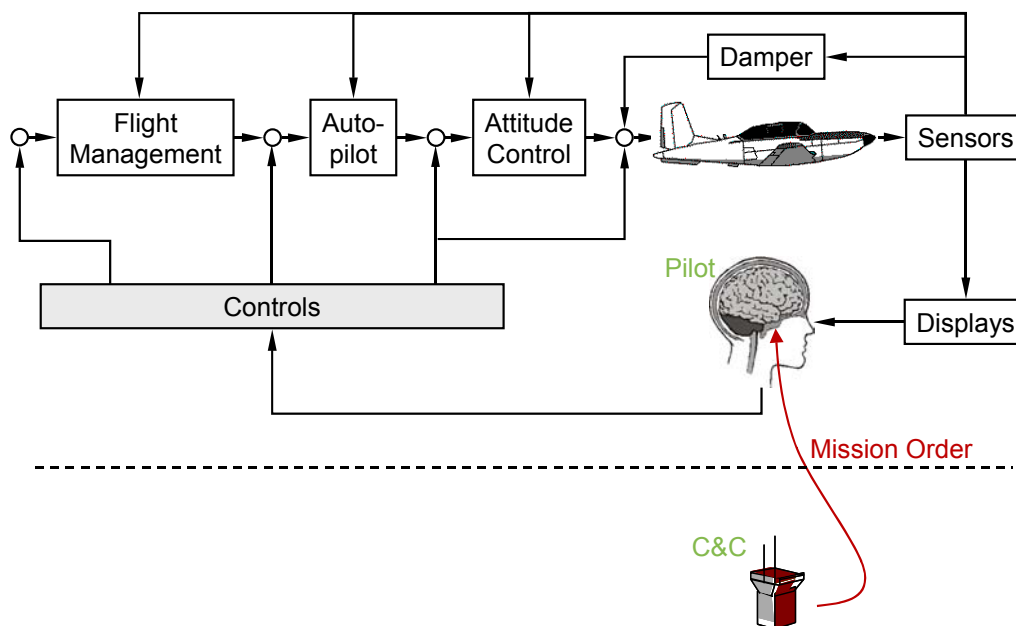


Figure 5-6: Conventional Guidance and Control System (Manned A/C).

While the pilot is controlling and supervising his machine, he himself is supervised by some external authority such as any imaginable implementation of command and control. In many western leaderships, the interface between command and control and the local operators is implemented on the basis of the assignment of work orders, i.e., mission orders in our domain.

A major performance feature of an educated, trained, and well skilled operator is the capability of transforming this work order into a desired work result. This structure, though, is tightly related to the conception of the work system according to the previous sub-section.

Figure 5-7 shows a situation which emerges when the pilot is removed from the vehicle and placed somewhere else, e.g., in a ground control station. Again, this remote operator will receive a mission order from any superior command and control authority. Usually, the operator now will interact with the UAV by

passing a detailed mission plan, which has to be worked out on the basis of the mission order, to the vehicle. In the case of a fully automated system, this initial mission plan will be pursued by the vehicle by use of the available on-board technology. Usually, with conventional technology, exceptional situations on the mission level, such as occurring obstacles, changes in the tactical situation, or other constraining factors cannot be handled. As a result of a monitoring function of the ground operator adaptations of the mission plan or reversing to outer loop guidance commands may occur. Usually, there are a couple of restraining factors for the remote operation of the vehicle:

- Manual control of the inner loops may not be possible or desirable because of intolerable time delays in the data transmission with respect to the inner loop dynamics time constants. Thus, the remote operation heavily relies upon the availability, the performance and integrity of some specific guidance functions, such as auto-land, otherwise requiring manual interactions.
- Insufficient downlink bandwidth and/or incomplete sensor coverage, with respect to the task, can cause what may be called “keyhole perspective” [8] for the remote operator, potentially affecting the correctness or quality of his or her decisions.
- The availability of data link, i.e., the ability to monitor (via telemetry) or control (via telecommand) the vehicle remotely may be disturbed. As a result, no recognition of nor reaction to unexpected situations is possible any more on the human operator’s side.

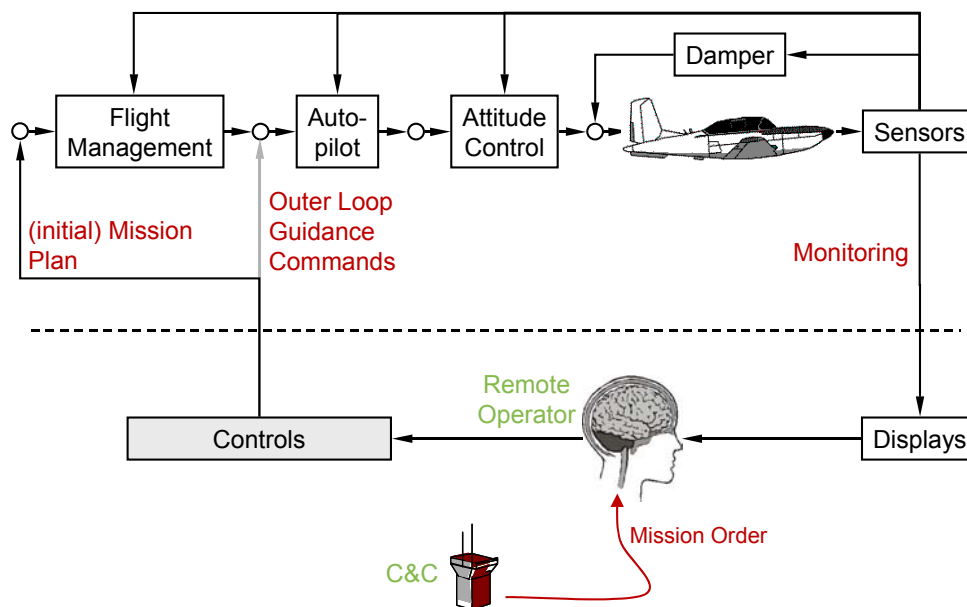


Figure 5-7: Conventional Guidance and Control System (Unmanned A/C).

What just has been elaborated for the flight guidance and navigation task holds true for other concurrent tasks of the operator, such as responding to a tactical environment or deploying mission related payload, as well. Air-to-air combat may serve as an extreme example, where sensory information from radar and identification equipment dictate the operator’s actions with regard to trajectory determination as well as weapon aiming and deployment, altogether facilitated by complex, highly automated systems themselves. Here again a complicated mixture of manual and supervisory control tasks can be observed. Automation technology is predominantly available on the manual control level, if at all.

Figure 5-8 tries to summarise the just now characterised situation with respect to conventional automation. In order to achieve a desired work result, running a machine or controlling a process, usually a more or less wide spectrum of tasks and related sub-tasks has to be worked on. This may include sub-tasks such as flying an aircraft, operating in a tactical scenario, managing avionics systems, and communicating with others, each of which involving automation to some specific extent. Although there may be “horizontal” interaction between automation involved in different task domains to some limited extent (e.g., the automatic performance of a terrain evasive manoeuvre, or the automatic transmission of radar tracks via tactical data link), the integration of information in order to pursue the overall task is performed by the human operator on a supervisory control level mostly. So, the interaction within the automation is predominantly vertically structured. A conventional flight guidance and control system (see Figure 5-6) is certainly a very good example, whereas the human operator is supposed to toggle between the different tasks horizontally on a supervisory performance level.

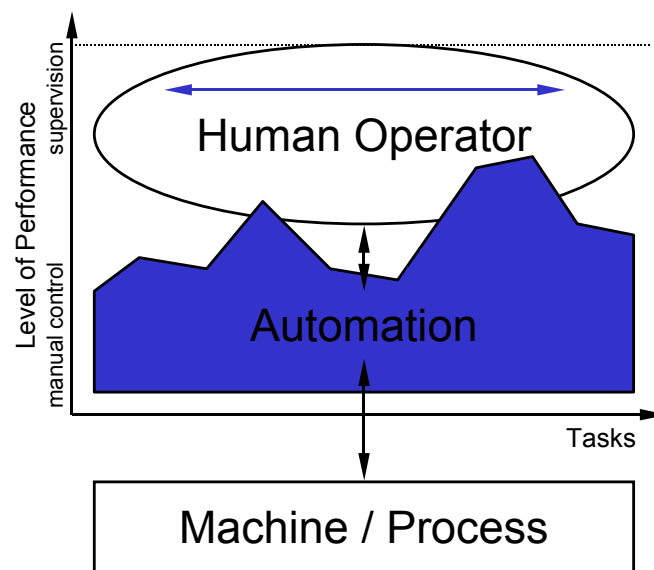


Figure 5-8: Organisational Structure of Conventionally, i.e., Hierarchically Automated Human-Machine Systems.

Having this rather simple organisational model of automation at hand the following section shall illuminate some technical pitfalls associated with this structure before some suggestions of improvements will be made.

5.2.3 References

- [1] REFA (1984). (Verband für Arbeitsstudien und Betriebsorganisation e.V.). Methodenlehre des Arbeitsstudiums. Teil 1: Grundlagen. Hanser-Verlag.
- [2] Onken, R. (2002, 7-9 October). Cognitive Cooperation for the Sake of the Human-Machine Team Effectiveness. In: RTO-HFM Symposium on The Role of Humans in Intelligent and Automated Systems. Warsaw, Poland.
- [3] Sheridan, T.B. (1987). Supervisory Control. In: G. Salvendy (Ed.). Handbook of Human Factors. Chapter 9.6. pp. 1245-1268. John Wiley & Sons. New York.

- [4] Sheridan, T.B. (1992). Telerobotics, Automation and Human Supervisory Control. MIT Press.
- [5] Rouse, W.B. (1980). Systems Engineering Models of Human-Machine Interaction. Elsevier North Holland.
- [6] Wickens, C.D. (1992). Engineering Psychology and Human Performance. Second Edition. HarperCollins Publishers.
- [7] Brockhaus, R. (2001). Flugregelung. Zweite Auflage. Springer.
- [8] Woods, D.D. (1984). Visual Momentum: A Concept to improve the cognitive coupling of person and computer. In: International Journal of Man-Machine Studies. 21, 229-244.

5.3 PROBLEM DEFINITION

The last section introduced one possible approach to how automation in human-machine systems could be looked at. Without being too specific on particular mission systems, some peculiarities of current, i.e., conventional automation systems have been deduced. This section provides a closer look upon problems which may arise in use of this automation approach. In the further pursuit of this section a possible perspective of future automation technology will be given, finally ending up with some very particular requirements to be implemented before such systems will be put into work.

5.3.1 Shortfalls with Conventional Automation

It has long since been known that erroneous human action is the predominating factor in aviation accidents, however, it is fair to state that many of these human errors are caused by over-demands (see grey line in Figure 5-9) on the pilot's resources [1], the latter representing the natural limiting factor for performance (see straight blue line in Figure 5-9). In order to overcome this situation the introduction of automation as described above was most beneficial in many situations, which otherwise could not be handled (see green line in Figure 5-9). On the other hand, new types of latent overtaking-prone situations appeared with the increased introduction of automated functions [Onken, 1999] (see red line in Figure 5-9).

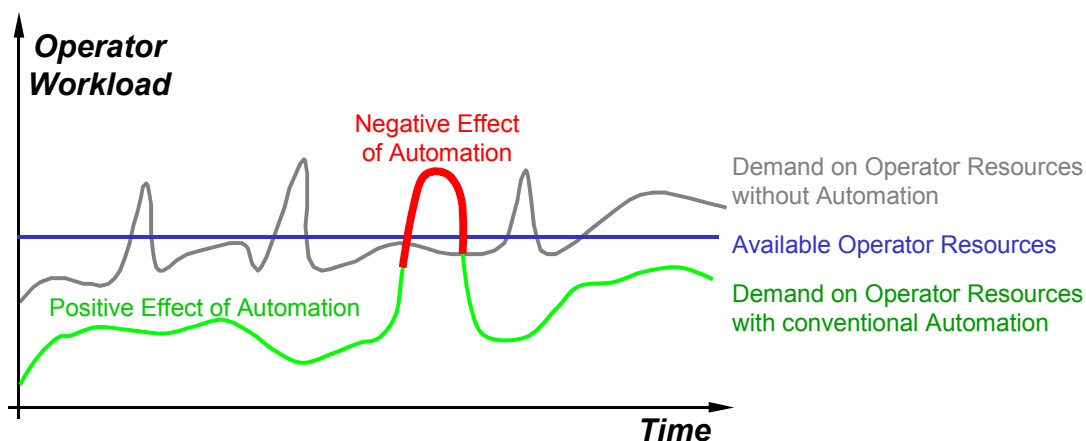


Figure 5-9: Operator Overload Caused by Conventional Automation.

Charles E. Billings investigated typical shortfalls of current aviation automation [2], with a particular view upon the human interaction with automation. According to Billings, the most critical design factors are complexity (Will the extent of the automatic function be fully understood by the human operator?), brittleness (Will the complex automation be fit for any imaginable situation or purpose?), opacity (Will the automatic execution provide sufficient and intelligible feedback to the human operator?), and literalism (Will the automation understand the human operator's control actions as 'naturally' as they are meant?). Generally spoken, Billings' answer to these questions with respect to current automation is "No", resulting in a situation which is usually referred to as clumsy automation [3].

Figure 5-10 explains the situation by use of the organisational structure of conventional automation with respect to task allocation between automation and the human operator as introduced previously (see Figure 5-8). Obviously, the classical task allocation suffers from some typical difficulties [23].

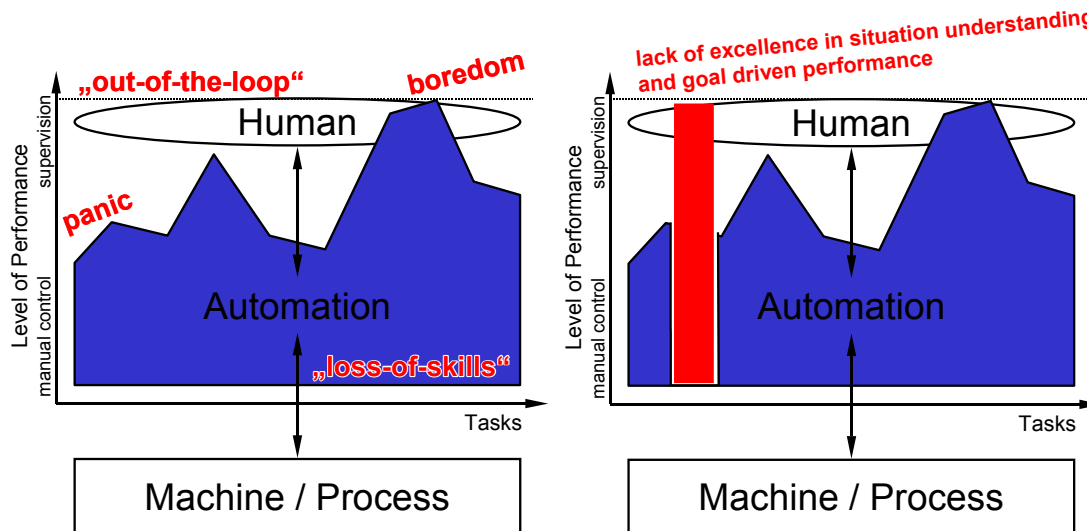


Figure 5-10: Shortfalls with Conventional Automation.

In particular under the assumption of increasing complexity of automation, the human operator is almost completely separated from the underlying process. The long term problem of loss of skills, i.e., erosion of competence, in supervisory control has been widely reported on, e.g., [4,5]. Within the same class of difficulties the human-out-of-the-loop problem represents the corresponding short term issue, addressing situations where operators almost fully rely upon the automation performance to an extent that any abnormal situation will inevitably cause human overload and erroneous action. [6] states:

“[...] by taking away the easy parts of his task, automation can make the difficult parts of a human operator's task more difficult.” [6]

Quite closely linked with Billings' notion of brittleness is the perception that conventional automation will usually not be able to recover from undesired situations induced by malfunctions, faulty operations or just the unexpected. The major reason for this limpness of the system is its lack of excellence in situation understanding and goal driven performance on the machine side, i.e., the missing capability of current automation systems to perform on a supervisory level in order to pursue the overall goals of the work system. As a good explanation for this circumstance the example of a simple autopilot function may serve [24].

Once activated, an “altitude acquire” function will pursue its specific sub-task of capturing a flight altitude pre-selected by the pilot in an almost perfect manner, no matter what may be of any relevance otherwise, e.g., ground or traffic proximity, exposure to enemy radar, or faulty demand setting or mode selection by the pilot in the sense of for instance a misinterpreted ATC clearance. So, automation offers a dedicated set of more or less independent functions, each of which being responsible for a particular sub-task. The situation can get even more precarious when these functions start getting linked horizontally without that being transparent to the human operator (i.e., opacity due to [Billings, 2]). Modern flight management systems often bear this characteristic, but still, conventional automation is not at all capable of performing any higher decision loop in the sense of supervisory control.

5.3.2 Perspectives of Future Automation

As an essence from the last sub-section, automation complexity can be seen as the most critical issue. To begin with, complex automation used to be the key to a major increase in mission effectiveness and flight safety (see Figure 5-11). Due to limited resources and capabilities on the human operator’s side, a further increase of automation complexity has no longer been beneficial in terms of these productivity factors (see Figure 5-11). Obviously, automation became too complex to be reliably handled by human operators. The reason for this seems to be found in the unpredictability of the machine’s behaviour due to inconsistencies between the machine function and the human operator’s mental model of it. Conventional automation itself, in the first place meant to be an operation-assisting means, became a complex element within the already complex work system.

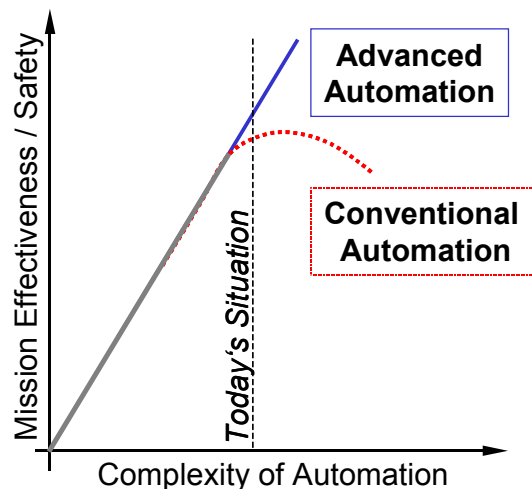


Figure 5-11: Perspectives of Future Automation.

In order to tackle this problem a new approach to automation has to be introduced into work systems. Figure 5-11 illustrates the vision of further increasing the productivity factors effectiveness and safety by advanced automation at the cost of furthermore complexity, but how shall this “advanced automation” be shaped?

Figure 5-12 tries to illustrate some first ideas in order to overcome the problems with conventional automation described earlier. Advanced automation shall not displace the human operator in a work system, but share the tasks in a close-partner work relationship. Task allocation shall not be static, but may be adapted to the current

situation's needs. This includes the facilitation of redundancy in functions in principal by at least a partial overlap in capabilities with respect to the task spectrum. The responsibility of automation (not necessarily authority) shall be extended to the supervisory control level, i.e., automation shall be enabled to perform certain tasks under consideration of the overall work task of the work system. Thereby, particularly brittleness will be tackled. Coordination and communication with such an automation system shall be supported on all performance levels, i.e., reaching from detailed low level information (reducing opacity of the machine solutions) up to abstract human-like information exchange on the supervisory level (tackling literalism of the automation). In general, it may be accepted that this approach to cognitive coupling [7] can be a contributing factor to the mitigation of disadvantageous complexity effects.

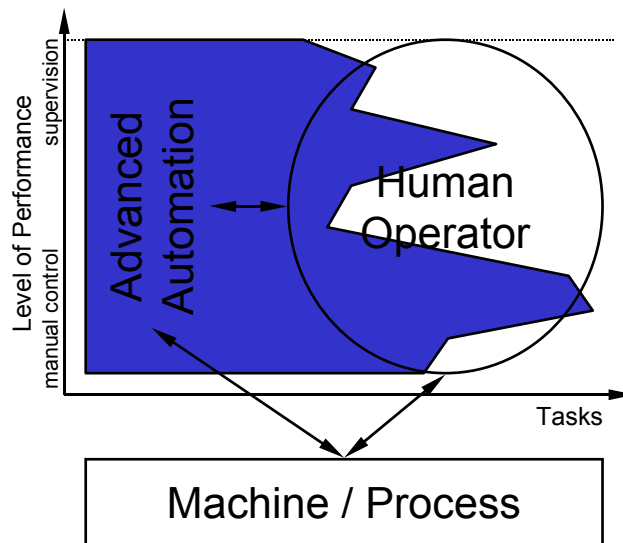


Figure 5-12: Co-operative Structure of Human-Machine Systems with Advanced Automation.

5.3.2.1 Cognitive Automation

An entity enabled to exhibit the aforementioned behaviour facets shall be referred to as Artificial Cognitive Unit (ACU) [24]. As indicated above, supervision and co-operation, as accomplishments of a machine system, require special capabilities. These capabilities were combined within the notion of such an Artificial Cognitive Unit. Obviously, the performance feature of cognition is the core element which has to be dealt with in order to design such an ACU. From the point of view of the discipline of cognitive psychology (e.g., [8,9]) human, i.e., natural cognition can be described by considering:

- Perception and allocation of attention;
- Knowledge representation and memory;
- Problem solving, reasoning and decision making;
- Language comprehension and its generation; and
- Learning and the development of expertise.

The availability of at least some of these aspects of cognition are the necessary pre-requisite to perform the supervisory control task (compare Sheridan, [26]) with respect to the compliancy with the overall work task.

Figure 5-13 shows the work system, according to Figure 5-3, with the human operator mimicked by an ACU. In this configuration the ACU represents all the performance requirements found to be attributed to the human operator earlier on, i.e., the performance of decision-making, problem-solving and supervision of the operation-assisting means and the work object in order to comply with the overall work task. The major difference is that the ACU is no longer invariant in terms of performance characteristics like its human archetype, but on the other hand, there has to be found a way how to design it according to the abovementioned requirements.

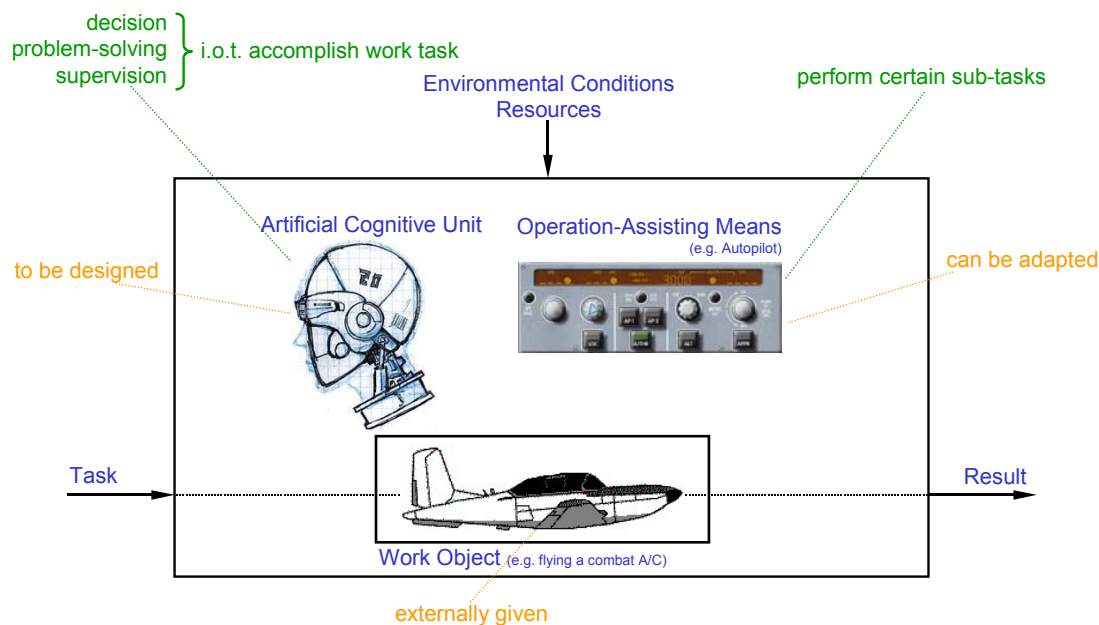


Figure 5-13: Artificial Cognitive Unit (ACU) Mimicking Human Operator in a “Work System”.

Strictly, Figure 5-13 is not representing a work system any longer, since the presence of a human operator as part of the operating element is required by definition [25]. Such a system would be degenerated from the standpoint of “work”, just existing for its own sake and not serving any human purpose. As soon as the human is involved as the tasking and monitoring element, which is always the case, the human will be part of the work system. The implications of this statement shall be discussed in the subsequent paragraph.

5.3.2.2 Automatic and Autonomous Performance

The (theoretical) configuration depicted in Figure 5-13, where the system is functioning (i.e., transforming the work object, e.g., flight, according to a work task into a desired work result) independently from any human intervention, can be referred to as being an autonomous system with respect to that particular work task. For this definition of autonomy a crucial factor is that a full work system is considered. Automated part-tasks, such as autopilot functions, working independently from human intervention likewise, are considered to be automatic.

Figure 5-14 [10] has to be understood in connection with the Figures 5-6 and 5-7. It shows the separation of automatic and autonomous systems from a more general point of view. The framed elements in Figure 5-14 form the considered work system.

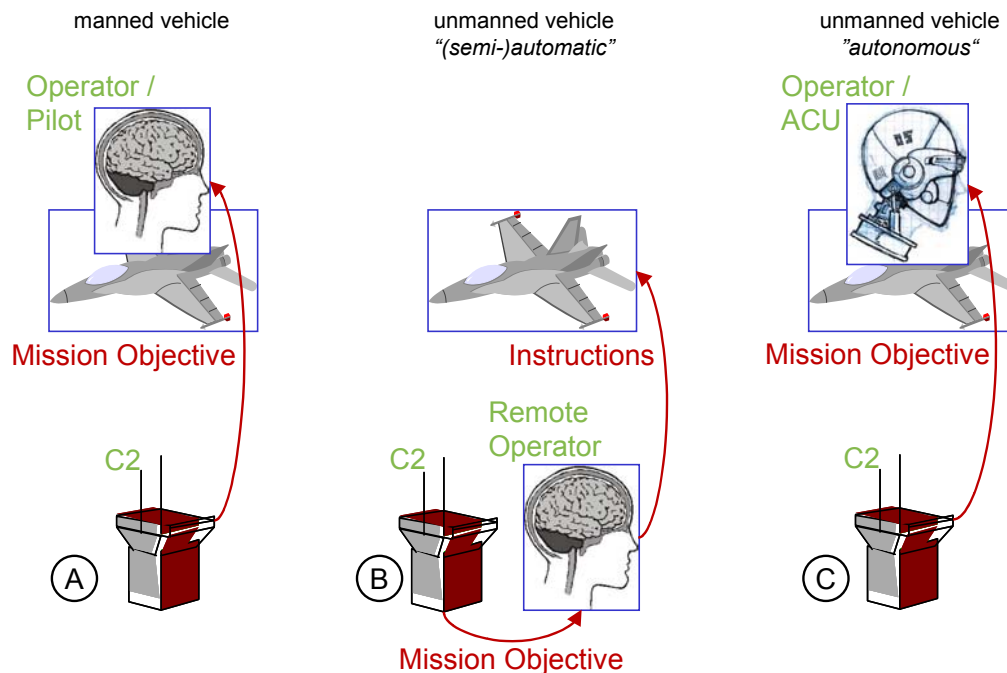


Figure 5-14: Comparison between Automatic and Autonomous Mission Accomplishment (Framed Elements Form Work System).

In case A of Figure 5-14 the work system is consisting of a human operator (pilot) and the vehicle, the latter representing the work object and the operation-assisting means, i.e., the conventional setup of a manned vehicle. In this configuration the operation-assisting means will provide diverse automatic functions. Having conventional manned vehicles or aircraft, an external command and control unit works out a mission order as a representation of the desired mission objective and passes it to the operator, who accomplishes the mission. Such a work system acts autonomously and co-operatively, depending on the current situation, the goals, the system's and operator's capabilities and resources.

Case B of Figure 5-14 represents the solution of conventional automation to the guidance of an uninhabited vehicle (compare Figure 5-7). In this setup the work system is spatially dislocated, bearing the aforementioned restraining factors for remote operation. The vehicle itself may be considered as being semi-automatic in the case of loose supervision or even fully automatic if no monitoring or supervision is desired at all. Such a vehicle typically has no 'on-board intelligence', and therefore, will accomplish a mission automatically. In some occasions, if there is a person on ground acting as a remote operator within the guidance loop, he has some influence on the actions of the vehicle during operation and the vehicle acts partially automatically. Otherwise, the person takes more the role of a supervisor, who usually provides the vehicle with pre-planned instructions, possibly including some action alternatives. How adequate an automatic vehicle reacts to a situation change depends in case of operator-guided operation on whether the operator gets enough information about the situation in which the vehicle is located. If a vehicle operates fully automatically, it can only react to situation changes, which were foreseen by the operator.

Case C of Figure 5-14 is the situation where an autonomously performing work system is only consisting of machine elements, i.e., the vehicle including operation-assisting means and the ACU, which is capable of generating human-like behaviour. Exclusively in this configuration the remote agent (i.e., the vehicle and its

guidance) forms an autonomous entity itself. Having this capability on-board several vehicles with partially overlapping (i.e., partly equal and partly different) resources and capabilities, it becomes possible to have a mission accomplished autonomously and co-operatively with an external supervisor providing an overall mission objective to all of them. [10]

5.3.2.3 Cognitive Automation as Part of the Operation-Assisting Means

In a traditional sense the human operator provides capability of cognition within a conventional work system, whereas the operation-assisting means do not. As an alternative to full autonomy without human intervention a configuration, where an artificial cognitive component in addition to the human operator might be introduced into the work system.

Figure 5-15 [24] shows the ACU being part of the operation-assisting means in an otherwise conventional, manned work system setup.

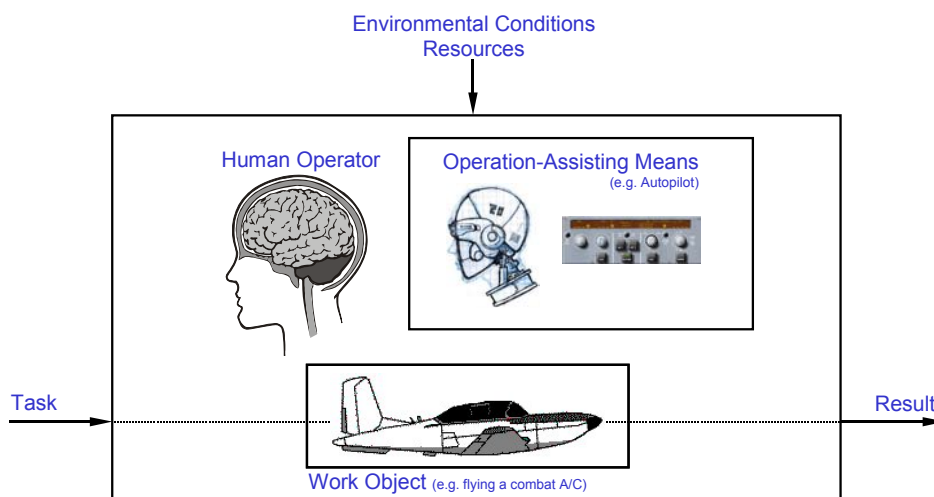


Figure 5-15: Work System with ACU in Configuration “Cognitive Automation as Part of Operation-Assisting Means”.

“As opposed to conventional automation, cognitive automation works on the basis of comprehensive knowledge about the work process objectives and goals [...], pertinent task options and necessary data describing the current situation in the work process. [...] Making use of these capabilities in terms of operation-assisting means in the work system, it has no longer to be the exclusive task of the [human] operator to monitor the process subject to the prime work system objectives.” [24]

In the case of cognitive automation incorporated into the operation assisting means the vision of a “cognitive autopilot”, as opposed to the conventional autopilot mentioned earlier on, would certainly perform superiorly. Once activated, a “cognitive altitude acquire” function would check the mode selection and the demand setting against the context of the current mission task. It would notice ground or traffic proximity, or maybe exposure to enemy radar. It would conclude that these conditions will result in loss of the mission or even disaster. Finally, it would work out an appropriate solution, either by indicating to the human operator the disturbance or by suggesting or even performing corrective actions.

This is pretty much the basic idea of a cognitive assistant system. Several research activities proved this concept more or less recently, the Cockpit Assistant System CASSY [11], the Crew Assistant Military Aircraft CAMA [12,13], and the Tactical Information and Mission Management System TIMMS [14]. Some more information on these projects will be given at the end of this chapter. Onken summarises the requirements for this class of systems:

“(1) It must be ensured the representation of the full picture of the flight situation, including that the attention of the cockpit crew is guided towards the objectively most urgent task or sub-task as demanded in that situation.

(2) A situation with overcharge of the cockpit crew might come up even when situation awareness has been achieved by the pilot crew. In this case the assistant system has to transfer the situation into a normal one which can be handled by the crew in a normal manner.” [15]

In these so-called two basic requirements for human-machine interaction the way is paved already for the next step in the integration of cognitive automation in a work system, in the sense of cognitively facilitated human-machine co-operation as another alternative work system configuration.

5.3.2.4 Co-operative Automation as By-Product of Cognitive Automation

As opposed to mere interaction, co-operation has particular characteristics. Co-operating units in a work system pursue additional goals. Billings [2] formulates respective design principles for human-machine co-operation in the context of human centred design:

The human operator must be

- Actively involved;
- Adequately informed; and
- Able to monitor the automation assisting him.

The automated systems must

- Be predictable; and
- Also be enabled to monitor the human operator.

And,

- Every intelligent system element must know the intent of other intelligent system elements.

Billings, though, does not offer a solution how the intelligent machine elements shall be designed, yet. He does not bear machine-machine co-operation in mind, either.

Figure 5-16 [24] shows a work system setup, where the human operator and the ACU form a team. In this configuration the ACU has reached

“[...] the high-end authority level for decisions in the work system, which was, so far, occupied by the human operator alone.” [24]

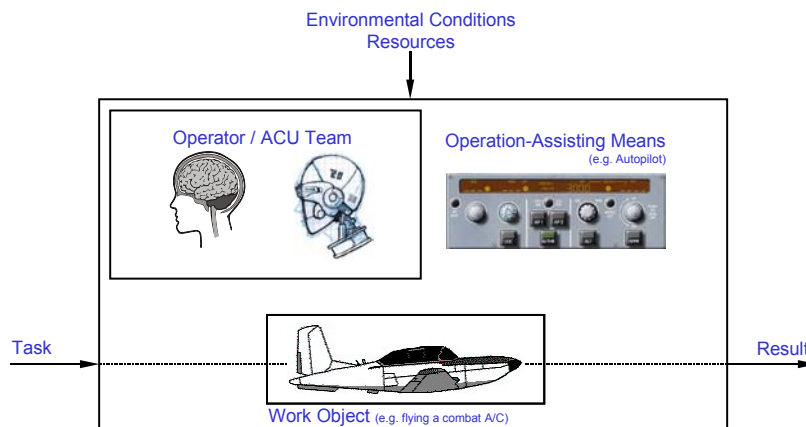


Figure 5-16: Work System with ACU in Configuration “Co-operative Automation”.

As a consequence of this consideration each of the team members has to have the ability to carry out all tasks, which might be crucial for the performance of the overall work task. A crew co-ordination concept, very similar to one examined for human-human cockpit teams [3,16], has to be developed.

5.3.3 Technological Challenges

In the previous section the introduction of artificial cognitive capabilities in a work system was discussed. The perspective of this advanced automation technology approach is to overcome current problems with clumsy systems in human-machine co-operation, in order to facilitate machine autonomy without human intervention, and to support human operators in demanding tasks, which tend to overload human resources. The term of an Artificial Cognitive Unit (ACU) has been introduced, so far without explaining, how such a system element shall be constructed.

Figure 5-17 visualises the various technological challenges to be borne in order to implement such a system:

- **Comprehensive situation perception:** Figure 5-5 shows that in principle the human operator on-board has access to information (environmental stimuli) which is offered to him in addition to the information from his vehicle systems. The human operator is able to look out of the window of his vehicle; he can hear environmental noise or follow the voice communication on the radio. He can sense structural vibrations of his vehicle and even smell smoke in the cabin, however, the most important point is probably that the human operator has the principal capability to understand most of these perceptions and put them into the context of previous experiences. Conventional automation is lacking most of these abilities, and thereby, has no access to a wide spectrum of environmental information relevant for crucial decisions. In order to facilitate cognitive behaviour in a machine system the ability to perceive the environment has to be ensured. Dickmanns and his research group contributed very substantial work in the area of computer vision for autonomous road vehicle guidance (e.g., [17]).
- **Cognitive capabilities:** The next step after a successful perception of the world will be the deduction of rational behaviour on the basis of the gathered information. Therefore, further cognitive capabilities (of course, perception is a cognitive capability itself already) will be needed, both, on the human operator's side as well as on behalf of the machine. What humans can do seemingly effortlessly has to be given to the automation by design. Automation shall be enabled to build up a mental model of the surrounding world, which can be understood as the comprehension of the situation and its projection into the future (e.g., [18] as one point of view). The so-gained situational

knowledge shall be adequately represented in memory (e.g., [19] or [20] as two classical sources). On the basis of this situation specific knowledge and other pre-recorded knowledge, problem-solving and decision-making shall be performed in order to achieve certain goals. The modelling of this component of cognition will be the main subject of the next section of this chapter, resulting in the theory of the Cognitive Process [24].

- **Human-machine interaction:** Having an intelligent unit within the work system, which is enabled to gather and understand the entire situation, to make decisions and to exhibit rational and goal-oriented behaviour, it will be necessary to make it interact with the human operator. First of all, appropriate communication channels have to be found. A system designed to perform on the higher levels of cognition certainly offers the principal opportunity to use language as communication code [21], besides others. Furthermore, an appropriate co-ordination technique has to be found in order to facilitate a fruitful co-operation aiming upon the accomplishment of a common mission objective. In the long term, intelligent machines shall appreciate other intelligent agents in their environment, either human or artificial, as such. In this case, co-operation will be an additional behaviour of a machine, based upon cognitive capabilities [10].
- **Level of automation and authority:** Like with human teams, the question of the allocation of tasks and authorities has to be answered for human-machine teams, as well as for machine-machine teams. Weiner [3] investigated the issue of crew resource management for the aviation domain. Billings [2] made his suggestions for human centred aircraft automation design and human-machine co-operation. Taylor [22] worked on the problem of allocation of authorities within a human-machine team with the aim to provide the necessary and sufficient levels of authority for the task automation – but still, only the existence of artificial cognitive team mates will reveal the critical questions in the context of the allocation of tasks and authority, which have to be tackled.
- **Paradigm shift:** Finally, users, consumers, designers, companies, procurement officers, and customers, who are involved in the introduction of a new automation technology in their specific way, have to reconsider the issue of the evolution of personal, social, and economic factors, which comes along with such a process. In some cases a paradigm shift will be inevitable. At the very deep end of the chain, training issues related with the handling of somehow intelligent machinery will certainly come up.

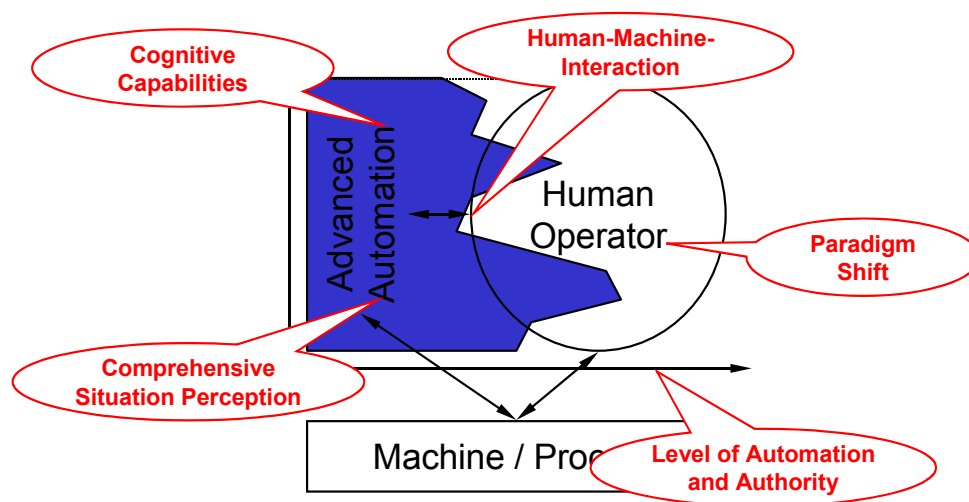


Figure 5-17: Technological Challenges in Advanced Automation.

The following section “Approaching Cognition” will be dedicated to the analysis of cognitive capabilities of humans. On the basis of this, an overview over information technology approaches to artificial cognition will be given. As a result, the so-called Cognitive Process (CP) as a theoretical approach to machine intelligence will be introduced.

5.3.4 References

- [1] Onken, R. (1999). The Cockpit Assistant Systems CASSY/CAMA. In: World Aviation Congress 1999. 99WAC-91. San Francisco, October.
- [2] Billings, C.E. (1997). Aviation Automation: The Search for a Human-Centered Approach. Lawrence Erlbaum.
- [3] Wiener, E.L. (1989). Human factors of advanced technology (“glass cockpit”) transport aircraft (Technical Report 117528). Moffett Field, CA: NASA-Ames Research Center.
- [4] Wiener, E.L. and Curry, R.E. (1980). Flight Deck Automation: Promises and Problems. In: Ergonomics. 23(10):995-1011.
- [5] Wiener, E.L. and Nagel, D.C. (1987). Human Factors in Aviation. Academic Press. 1988.
- [6] Bainbridge, L. (1987). Ironies of Automation. In: New Technology and Human Error. Eds.: Rasmussen, Duncan, Leplat. Wiley.
- [7] Rasmussen, J., Pejtersen, A.M. and Goodstein, L.P. (1994). Cognitive Systems Engineering. Wiley.
- [8] Anderson, J.R. (2000). Cognitive Psychology and its Implications. Fifth Edition. Worth Publishers.
- [9] Eysenck, M.W. (1993). Principles of Cognitive Psychology. Lawrence Erlbaum Associates Publishers.
- [10] Ertl, C. and Schulte, A. (2004, September). System Design Concepts for Co-operative and Autonomous Mission Accomplishment of UAVs. In: Deutscher Luft- und Raumfahrtkongress. Dresden, GE. 20-23.
- [11] Prévôt, T., Gerlach, M., Ruckdeschel, W., Wittig, T. and Onken, R. (1995). Evaluation of intelligent on-board pilot assistance in in-flight field trials. In: 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems. Massachusetts Institute of Technology, Cambridge, MA. June.
- [12] Walsdorf, A., Onken, R., Eibl, H., Helmke, H., Suikat, R. and Schulte, A. (1997). The Crew Assistant Military Aircraft (CAMA). In: The Human-Electronic Crew: The Right Stuff? 4th Joint GAF/RAF/USAF Workshop on Human-Computer Teamwork. Kreuth, GE. September.
- [13] Schulte, A. and Stütz, P. (1998). Evaluation of the Crew Assistant Military Aircraft (CAMA) in Simulator Trials. In: NATO Research and Technology Agency, System Concepts and Integration Panel. Symposium on Sensor Data Fusion and Integration of Human Element. Ottawa, Canada. September 14-17.

- [14] Schulte, A. (2002). Cognitive Automation for Attack Aircraft: Concept and Prototype Evaluation in Flight Simulator Trials. In: International Journal of Cognition Technology and Work. MS No. 94, Vol. 4 No. 3, Pages 146-159. Springer London Ltd.
- [15] Onken, R. (1994). Basic Requirements Concerning Man-Machine Interactions in Combat Aircraft. Workshop on Human Factors/Future Combat Aircraft. Ottobrunn, Germany. October.
- [16] Wiener, E.L. (1993). Intervention strategies for the management of human error. (NASA Contractor Rep. No. 4547) NASA Ames Research Center, Moffett Field, CA.
- [17] Dickmanns, E.D. (2002). Expectation-based, multi-focal, saccadic (EMS) vision for ground vehicle guidance. In: Control Engineering Practice 10 (2002) , pp. 907-915. Pergamon Elsevier Science.
- [18] Endsley, M.R. (2000). Theoretical underpinnings of situation awareness: A critical review. In: Endsley & Garland (Eds). Situation Awareness Analysis and Measurement. Lawrence Erlbaum Associates.
- [19] Quillian, M.R. (1966). Semantic Memory. Bolt, Beranek and Newman. Cambridge, MA.
- [20] Minsky, M. (1974). A Framework for Representing Knowledge. Memo 306. Cambridge, MA. MIT AI Lab.
- [21] Gerlach, M. and Onken, R. (1993). Speech Input/Output as Interface Device for Communication between Aircraft Pilots and the Pilot Assistant System CASSY. In: Applications of Speech Technology. Joint ESCA-NATO/RSG 10 Tutorial and Workshop. Lautrach, GE.
- [22] Taylor, R.M. (2001). Cognitive Cockpit Engineering: Pilot Authorisation and Control Tasks. In: 8th Conference on Cognitive Science Approaches to Process Control (CSAPC). Munich.
- [23] Schulte, A. (2003). Systems Engineering Framework Defining Required Functions of Un-inhabited Intelligent Vehicle Guidance. In: NATO RTO. Human Factors and Medicine Panel. Task Group HFM-078 on Unmanned Military Vehicles: Human Factors in Augmenting the Force. Leiden, NL. 10th – 13th June.
- [24] Onken, R. (2002). Cognitive Cooperation for the Sake of the Human-Machine Team Effectiveness. In: RTO-HFM Symposium on The Role of Humans in Intelligent and Automated Systems. Warsaw, Poland. 7-9 October.
- [25] REFA (1984). (Verband für Arbeitsstudien und Betriebsorganisation e.V.). Methodenlehre des Arbeitsstudiums. Teil 1: Grundlagen. Hanser-Verlag.
- [26] Sheridan, T.B. (1992). Telerobotics, Automation and Human Supervisory Control. MIT Press.

5.4 APPROACHING COGNITION

In the previous sections the term “cognition” has been used rather sloppy in the sense of a particular human capability, and, hopefully, of a future machine function. This section shall sort things out in terms of how humans perform and how a machine has to be constructed in order to exhibit intelligent behaviour, likewise. “Intelligence”, a term which can be replaced by “cognition” in most cases in this context, is defined rather

vaguely defined in habitual language use, although being a rather valid concept in psychology. Besides many other definitions, Morris [1] gives:

“Intelligence [... is ...] a general term encompassing various mental abilities, including the ability to remember and use what one has learned, in order to solve problems, adapt to new situations, and understand and manipulate one’s environment.” [1]

Nowadays intelligence or cognition is no longer exclusively considered by psychology, but is subject to the interdisciplinary field of “cognitive science”, which is influenced by philosophy, psychology, neuroscience, linguistics, anthropology, and, of course, by computer science and information technology. In this enumeration the last discipline seems to be of some particular interest, because it facilitates to prove the validity of theories by modelling and simulation. New concepts emerging in the field of Artificial Intelligence (AI), a field of computer science that attempts to develop intelligently behaving machines [Anderson, 2000], influenced the cognitive psychology, and vice versa [2].

Many approaches dedicate themselves to the exploration of the underlying processing structure, as opposed to the principles of behaviourism, which was a rather strong trend in the early 20th century psychology, only being concerned with the externally observable behaviour of a human.

Figure 5-18 depicts the different approaches, the one of the behaviourism (top), and the alternative modelling view considering the internal processing (bottom). In both cases, the information processing paradigm (input → processing → output) is appropriate to characterise the phenotype of the situation. The behaviourism searches for the input-output mapping of human behaviour, no matter how it will be implemented. Other modelling approaches focus on the description of the underlying processes, in order to expose the observed behaviour. In the subsequent few sections a brief overview will be given over approaches to the modelling of the processing mechanisms of human cognition. Behaviour, in turn, can be utilised in order to validate related models.

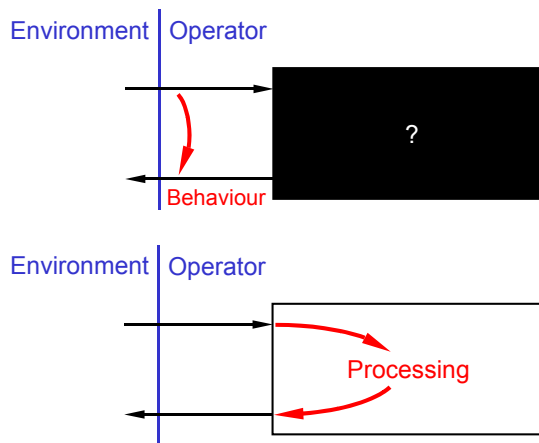


Figure 5-18: Modelling Behaviour or Processing.

5.4.1 Model of Human Performance

In order to open the window to the development of human-like performance features in terms of cognitive automation, the very well accepted model of human performance levels by Jens Rasmussen [3] will be

consulted, to begin with. The simplicity and intelligibility made this model, originally having its seeds in ergonomics research, quite popular in the circles of cognitive psychologists as well as amongst engineers. In fact, Rasmussen's model became the probably most common psychological scheme within the entire engineering community.

Without going into too much detail here (for a most detailed discussion refer to [3] and [26]), the model distinguishes between three levels of human performance, the skill-based, the rule-based, and the knowledge-based behaviour (see Figure 5-19). On the skill-based level highly automated control tasks will be performed, without any mental effort or consciousness. Typical for this level is the continuous control of the body in three-dimensional space and time. Most of this performance is carried out in feedforward control mode by pre-programming of stored sensor-motor patterns on the basis of task specific features. Typical behaviour on this level, like tracking a road, will be assembled by running a sequence of parameterised templates with some feedback control ratio for precision enhancement.

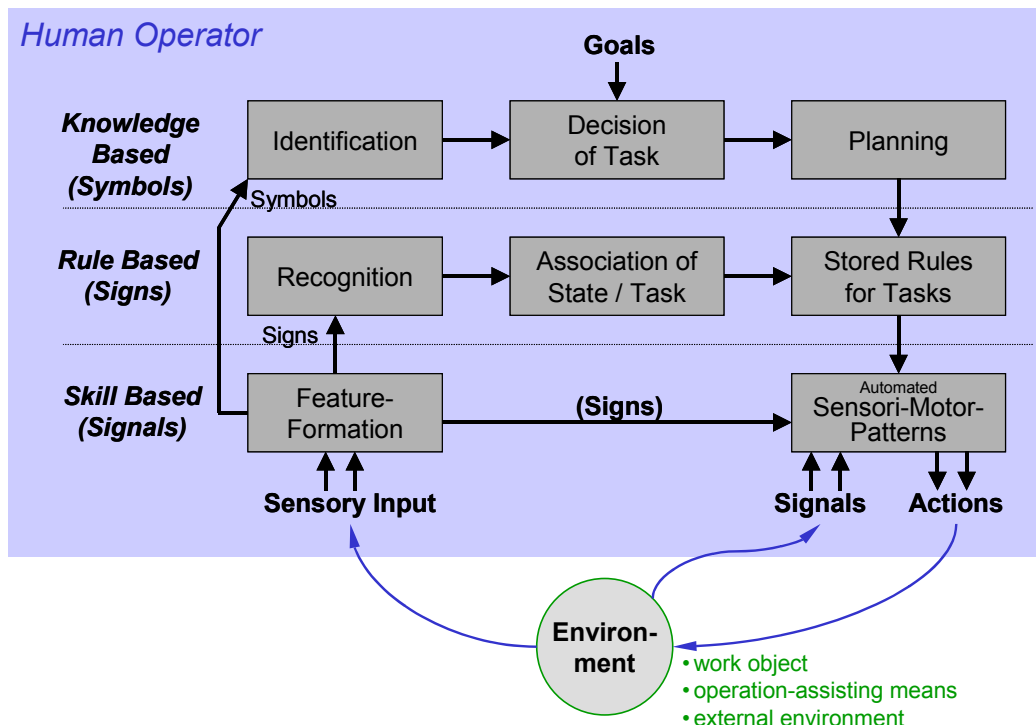


Figure 5-19: Rasmussen's Model of Human Operator's Performance Levels Linked to Environment.

On the rule-based level most of the everyday conscious action that we perform takes place in a strict feedforward control manner. Here, humans follow pre-recorded scripts and procedures in order to activate the appropriate sensori-motor patterns on the basis of the presence of clearly recognised objects characterising the prevailing situation. With training formerly rule-based performance tends to be dropped to the skill-based level. Rule-based performance is goal-oriented, although goals are not explicit, but encoded in the pre-conditions of the applicable rules.

The knowledge-based level will be entered in situations, where there are no applicable rules available in order to recognise objects or to determine the selection of action. This is the case when the situation requires the

preoccupation with a non-pre-defined problem. In this case general concepts have to be consulted in order to identify the situation, i.e., find similar or somehow related situations in previous experience. Goals derived from overall aims explicitly direct the tasking. Planning, i.e., problem-solving will be deployed in order to generate new scripts or procedures, which will be executed on the rule-based level. In general, problem-solving can be considered as a highly versatile process, incorporating strategies such as difference reduction and means-ends analysis [17] as well as search in problem space [4]. So-called mental models will be the knowledge basis for the highest performance level [3].

Although it is so common to the engineering community, because of its apparent use of clear functional blocks and their interrelations, Rasmussen's model deserves some interpretation from an information technology point of view. One reason for this is the improper handling of knowledge in the model. Most of the boxes represent a dedicated function or processing step (e.g., 'recognition', 'planning'). Only two particular boxes (i.e., 'stored rules for tasks' and 'sensori-motor patterns') represent knowledge, without having their individual functions specified. And finally, only one functional block (i.e., 'decision of task') makes use of an explicit knowledge basis ('goals'). From an information technology standpoint it would be desirable to modify the model according to the following guidelines, at least for a first step of advancement:

- Use boxes for functions or processing steps;
- Label the knowledge which is made use of in each box; and
- Label all inputs and outputs of the functional blocks.

The detailed discussion of this issue shall be the matter of forthcoming publications.

5.4.2 Modelling Approaches for Intelligent Machine Behaviour

As discussed above, the human performance can be decomposed in several high level cognitive functions, which rely upon certain a-priori knowledge. Besides the task-related a-priori knowledge, there are mechanisms necessary in order to process this knowledge. Highly related with these mechanisms is the form of representation of this knowledge. In parallel to the development of psychological performance and behaviour models as briefly discussed in the previous section there takes place the development of technological approaches to intelligent machine behaviour, each of which influencing and fertilising one another.

From a very global standpoint there can be identified two fundamentally different approaches, one strongly influenced by the idea of mimicking the human implementation of cognition in the brain (i.e., connectionism, artificial neural networks, sub-symbolic AI) [5], and the other being based upon models taken from information technology (i.e., symbolism, Artificial Intelligence) [2].

Besides those two main streams, early human factors research offered modelling approaches on the basis of control theory [18].

Figure 5-20 shows the principal approach of this class of approaches, modelling human behaviour by means of transfer functions. Typically, there were made a couple of structural assumptions, such as reaction time and neuromotor delay as inherent parameters and gain and anticipation as task-adaptable parameters. On the basis of such model structure quite successful parameter identifications could be performed, typically limited to various sensori-motor control tasks.

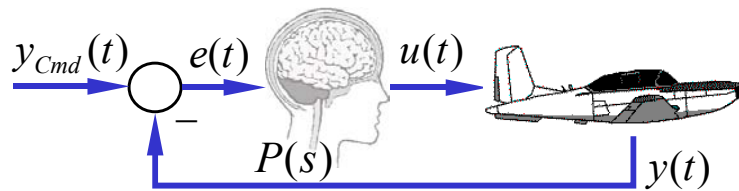


Figure 5-20: Model of Human Behaviour Motivated by Control Theory (i.e., Transfer Function).

Coming back to the aforementioned antithetic approaches of connectionism and symbolism one major difference can be identified in the way of knowledge representation. In the connectionism there is no separation existing between knowledge and its processing. Neither is knowledge in any way explicit, but spread over the weights of the connections between simple but numerous processing units (neurons). Each single weight provides a contribution to the knowledge persistent to the model without a particular allocation of meaning. The entirety of weights represents the entirety of a-priori knowledge. Many models provide learning mechanisms, either in supervised or unsupervised learning mode.

Symbolism, on the other hand, utilises explicit, meaningful symbols in order to handle knowledge. Processing architectures are derived from simple information processing paradigms, as depicted in Figure 5-21.

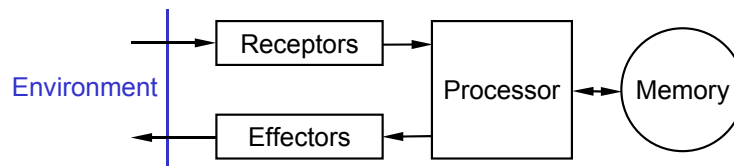


Figure 5-21: Model of Human Processing Motivated by Information Technology.

While the processor is almost independent from the task, the functionality is encoded in the knowledge persistent to the memory. The interface to the external world build dedicated receptors and effectors. The probably most famous, classical model of this kind is the so-called CMN-model [6] as shown in Figure 5-22.

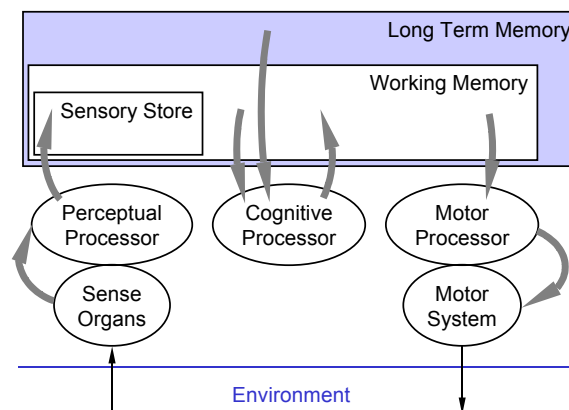


Figure 5-22: The Model Human Processor Adapted from CMN-Model.

The CMN-model in particular points out the assumed structure of the memory of the human and some performance features and limitations of its building blocks. The 7-chunk capacity limit of the working memory is probably one of the most acquainted proposition in this context. As principal concept of processing the so-called recognise-act cycle (RAC) (see Figure 5-23) is proposed.

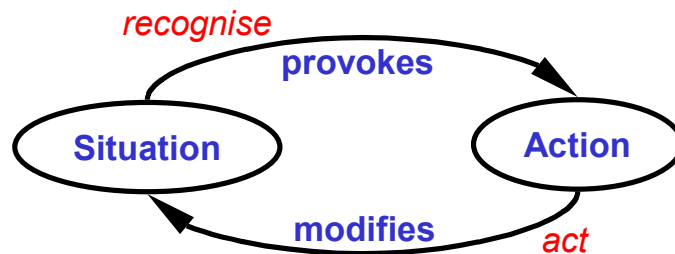


Figure 5-23: The Recognise-Act Cycle.

To characterise the activity of the cognitive processor, [6] state:

On each cycle, the contents of Working Memory initiate associatively-linked actions in the Long-Term Memory (“recognize”), which in turn modify the contents of Working Memory (“act”), setting the stage of the next cycle. [6]

The interface to the environment is through the working memory.

The so-called production systems (expert systems) predominantly follow the processing approach of the recognise-act cycle using mainly IF-THEN rules as knowledge representation form for heuristics and “rules of thumb”. Figure 5-24 shows the main building blocks of such a rule-based system (i.e., production system). The knowledge is stored in the rule base, the long-term memory of the architecture. Based upon the short-term (i.e., working) memory contents (i.e., internal states plus input from and output to the environment) according to their pre-conditions rules from the rule base will be selected as candidates for execution. After the solution of conflicts (in the case of, e.g., more than on applicable rules) the rule will be “fired”, i.e., the post-condition of the rule will be executed in order to modify the content of the short-term memory, either initiating a succeeding recognise-act cycle base on internal state changes, or evoking an action at the output.

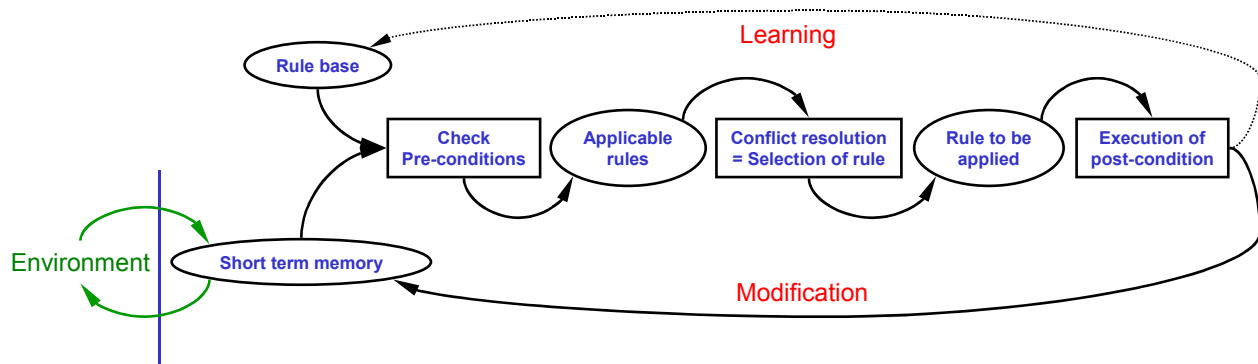


Figure 5-24: Architecture of a Rule-Based System (i.e., Production System).

Besides these very traditional approaches, predominantly relying on the use of rules as form of knowledge representation, many other kinds of knowledge representations evolved in the era of GOFAI (“Good-Old-Fashioned Artificial Intelligence”), most of which linked to symbolist approaches on one or the other way, e.g., semantic networks [19], conceptual dependency [7], frames/schemata [20], scripts [8], just to name the classical ones.

Besides these “classical” ones there are at least two more recent approaches important to be mentioned here, both of which being symbolic cognitive architectures meant to model intelligent performance:

- ACT-R [9] is used to model different aspects of human cognitive behaviour, i.e., to implement human-like behaviour. ACT-R has its starting point in creating a computational theory of human memory. It combines predominantly symbolic representations with sub-symbolic mechanisms, mainly to model human performance aspects such as the limited retrievability of knowledge.
- SOAR [10,4] is used to model an agent’s intelligent capabilities, i.e., to implement rational behaviour. SOAR has its roots in the attempt to understand the methodological and structural pre-requisites of human problem-solving and decision-making. Concerning knowledge representations, SOAR is a rule-based, i.e., a production system.

While the aforementioned architectures pair a still strong focus on knowledge representation with architectural aspects of cognition, some concurrent approaches capitalise upon mostly architectural views. Some of the most prominent approaches shall be brought up here:

- BDI (Belief-Desire-Intent)-Agents [11]: Agents are software constructs situated in a certain environment and interacting with it autonomously in order to achieve specific individual objectives. Applications are widely spread over various domains from data management over user interfaces and computer mediated collaboration to robotics. The BDI architecture suggests the usage of mental attitudes representing the informational (belief), the motivational (desire) and the deliberative (intent) state of the agent.
- RCS (Real-time Control System) [12]: RCS is a reference model architecture, suitable for real-time control problem domains, and therefore closely related to robotics. It focuses on intelligent control that adapts to uncertain and unstructured operating environments. The architecture provides a top-down hierarchical composition of processing nodes incorporating the cognitive functions of sensory processing, world modelling, value judgement and behaviour generation.
- Subsumption Architecture [13], representing the field of behaviour-based robotics, almost fully dismisses the notion of a mental world model. Instead, this architecture is strongly behaviour oriented, i.e., focussing on direct perception-action mappings facilitated by close couplings between sensors and actuators. More complex behaviours are assumed to emerge from simpler ones in a bottom-up manner. Symbolic representations are not part of this architecture.

As this very brief, and by no means complete, overview of modelling approaches for intelligent machine behaviour indicates, the research focus over the last three decades has been shifted from mostly method oriented approaches, e.g., how to represent knowledge, to somewhat more architecture focussed approaches.

When it shall come down to a systems engineering implementation of intelligent machinery, both aspects yet are of their particular importance, and therefore should be considered in a well balanced manner. The following sub-sections introduce the concept of the Cognitive Process [21,22,14], which comprises a theory based on cognitive psychology with a knowledge-based architecture.

5.4.3 The Cognitive Process as Approach to Cognitive Automation

Coming back to the aim of a co-operative structure of a human-machine system (as depicted in Figure 5-12), the notion of cognitive automation (as introduced in the Sections 5.3.2. ff.), and the technological challenge of providing cognitive capabilities to an Artificial Cognitive Unit (ACU) (as formulated in Section 5.3.3), we now want to take the findings on cognition (Section 5.4) into consideration in order to develop a theory-based architecture for intelligent machine behaviour. Findings from cognitive psychology and artificial intelligence shall be taken into consideration likewise.

The concept of a piece of automation being a team-player in a mixed human-machine team, or even a machine taking over responsibility for work objectives to a large extent, promotes the approach of deriving required machine functions from models of human performance. In Section 5.4.1 Rasmussen's model has been introduced.

When we look at conventional automation as discussed in the Section 5.2.2 and 5.3.1, in particular in the avionics domain, it mainly acts on a level which might be compared with the skill-based human performance level (e.g., flight control systems, autopilot systems). Some functionalities might be attributed to the rule-based (e.g., traffic collision avoidance systems) and few on the knowledge-based level (e.g., mission planning support in flight management systems).

On the other hand, not many automation systems can be identified, providing an understanding of the current situation in terms of recognition and identification, or considering goals, which are essential for the decision of what to do next in an unknown situation, as already discussed in Section 5.3.1.

In contrast to the conventional approach, cognitive automation aims for rationality in a human-like performance manner, without modelling typical human's shortcomings. Thus, all functions of Rasmussen's model have to be covered, including those already incorporated in conventional automation [14]. Figure 5-25 shows the main focus area for future developments aiming at cognitive automation, namely the implementation of a comprehensive situation understanding and goal-driven decision-making, as high level cognitive capabilities.

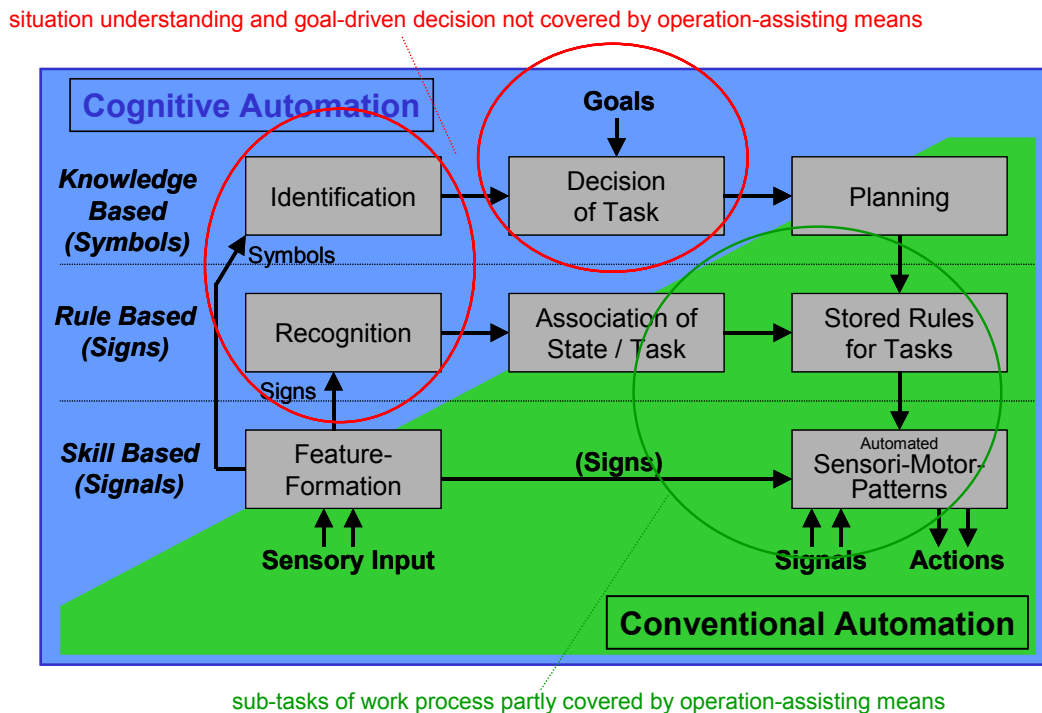


Figure 5-25: Conventional and Cognitive Automation Explained by Rasmussen's Model of Human Performance.

In order to achieve a system engineering framework, the main idea of Rasmussen's model, namely rule- and knowledge-based performance, is mapped into the so-called Cognitive Process (CP). The CP is an approach to modelling human information processing, which is suitable for providing human-like rationality [14,15]. As it is compatible with human cognition, and the generated behaviour is driven by goals, which are represented explicitly, it is well suited for the development of a cognitive system, which is part of a team consisting of artificial and/or human team mates.

Figure 5-26 shows the CP consisting of the body (inner part) and the transformers (outer extremities). The body contains all knowledge, which is available for the CP to generate behaviour. There are two kinds of knowledge: the 'a-priori knowledge', which is given to the CP by the developer of an application during the design process and which specifies the behaviour of the CP, and the 'situational knowledge', which is created at run time by the CP itself by using information from the environment and the a-priori knowledge. The functional units effectively processing knowledge are the above-mentioned transformers, which read input data in mainly one area of the situational knowledge, use a-priori knowledge to process the input data, and write output data to a designated area of the situational knowledge.

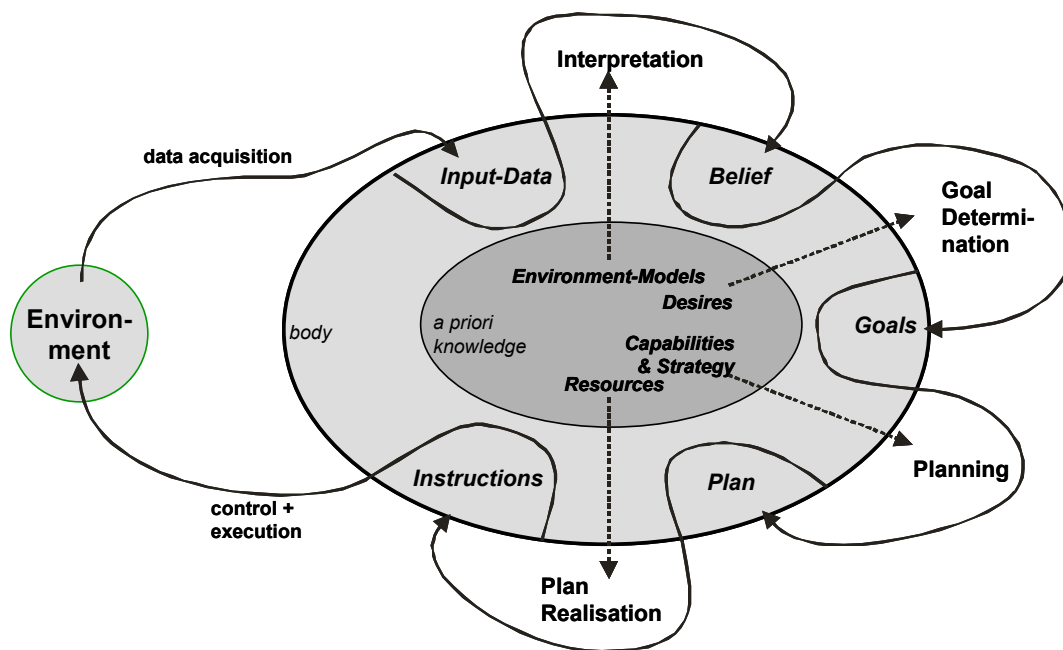


Figure 5-26: The Cognitive Process.

The following steps are performed by the CP in order to generate behaviour:

- Information about the current state of the environment (input data) is acquired via the input interface. In this context, the environment includes other objects in the physical world, e.g., another UAV or an obstacle, as well as the underlying vehicle of the CP. Therefore, the input data may for instance contain information about the current autopilot mode or pre-processed sensor information.
- The input data are interpreted to obtain an understanding of the external world (belief). The interpretation uses environment models, which are concepts of elements and relations that might be part of the environment, to build this internal representation.
- Based on the belief, it is determined, which of the desires (potential goals) are to be pursued in the current situation. These abstract desires are instantiated to active goals describing the state of the environment, which the CP intends to achieve.
- Planning determines the steps, i.e., situation changes, which are necessary to alter the current state of the environment in a way that the desired state is achieved. For this planning step, models of action alternatives of the CP are used.
- Instruction models are then needed to schedule the steps required to execute the plan, resulting in instructions.
- These instructions are finally put into effect by the appropriate effectors of the host vehicle. The resulting actions affect the environment, i.e., modify the physical world.

These functional units represent an application-independent inference mechanism, which processes application-specific knowledge. This knowledge-based design approach is of great advantage when implementing the CP: The inference mechanism has to be implemented only once, and can then be used for different applications.

It is desirable to reuse not only the inference mechanism, but also knowledge in different applications. For this purpose, a-priori knowledge has to be utilised in so-called ‘packages’, each of which represents a certain capability. As indicated in Figure 5-27, each package (depicted as horizontal layer) implements a capability which is designed according to the blueprint of the CP. Several packages together form the complete system. They are linked by dedicated joints in the a-priori knowledge and by the use of common situational knowledge. When looking vertically on the packages, a uniform structure of the a-priori knowledge and its order of usage in terms of processing steps according to the transformers of the CP can be recognised.

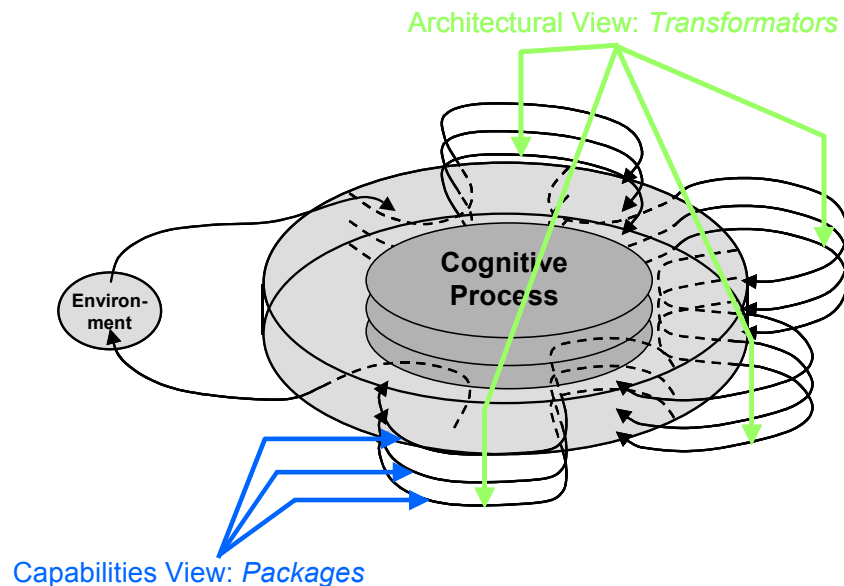


Figure 5-27: Representing Multiple Capabilities on Basis of the Cognitive Process.

5.4.4 References

- [1] Morris, C. (Ed.) (1996). Academic Press Dictionary of Science and Technology. Academic Press.
- [2] Newell, A. and Simon, H. (1972). Human Problem Solving. Englewood Cliffs, NJ: Prentice Hall.
- [3] Rasmussen, J. (1983). Skills, rules and knowledge, signal, signs and symbols, and other distinctions in human performance models. In: IEEE Transactions on Systems, Man and Cybernetics. SMC-13, pp. 257-266.
- [4] Newell, A. (1990). Unified Theories of Cognition. Harvard University Press. Cambridge, MA.
- [5] Rumelhart, D.E., McClelland, J.L. and the PDP Research Group (1986). Parallel Distributed Processing: Explorations in the Microstructure of Cognition, Volumes 1 and 2. Cambridge, MA: MIT Press.
- [6] Card, S.K., Moran, T.P. and Newell, A. (1983). The Psychology of Human-Computer Interaction. Lawrence Erlbaum Associates, Publishers. New Jersey.
- [7] Schank, R.C. (1975). Conceptual Information Processing. Elsevier. New York.

- [8] Schank, R.C. and Abelson, R. (1977). *Scripts, Plans, Goals, and Understanding*. Erlbaum Associates. Hillsdale, NJ.
- [9] Anderson, J.R. (1993). *Rules of Mind*. Erlbaum. Hillsdale, NJ.
- [10] Laird, J., Newell, A. and Rosenbloom, P. (1987). *SOAR: An Architecture for General Intelligence*. Artificial Intelligence, 33.
- [11] Rao, A. and Georgeff, M. (1995). *BDI Agents from Theory to Practice*. Technical Note 56. AAIL. April.
- [12] Albus, J.S. and Meystel, A.M. (2001). *Engineering of Mind: An Introduction to the Science of Intelligent Systems*. John Wiley & Sons, Inc.
- [13] Brooks, R.A. (1991). How to build complete creatures rather than isolated cognitive simulators. In: K. Van Lehn (ed.). *Architectures for Intelligence*. Lawrence Erlbaum Associates. Hillsdale, NJ.
- [14] Putzer, H. and Onken, R. (2003). *COSA – A Generic Cognitive System Architecture based on a Cognitive Model of Human Behavior*. In: *International Journal of Cognition Technology and Work*.
- [15] Ertl, C and Schulte, A. (2005). *Enabling Autonomous UAV Co-operation by Onboard Artificial Cognition*. In: *Proceedings of 1st International Conference on Augmented Cognition, in conjunction with HCI International, Las Vegas, USA, 22nd – 27th July*.
- [16] Rasmussen, J., Pejtersen, A.M. and. Goodstein, L.P. (1994). *Cognitive Systems Engineering*. Wiley.
- [17] Anderson, J.R. (2000). *Cognitive Psychology and its Implications*. Fifth Edition. Worth Publishers.
- [18] Rouse, W.B. (1980). *Systems Engineering Models of Human-Machine Interaction*. Elsevier North Holland.
- [19] Quillian, M.R. (1966). *Semantic Memory*. Bolt, Beranak and Newman. Cambridge, MA.
- [20] Minsky, M. (1974). *A Framework for Representing Knowledge*. Memo 306. Cambridge, MA. MIT AI Lab.
- [21] Onken, R. and Walsdorf, A. (2000). *Assistant Systems for Vehicle Guidance: Cognitive Man-Machine Cooperation*. In: *4th International Conference on IT for Balanced Automation Systems – BASYS 2000*. Berlin, Germany. 27-29 September.
- [22] Onken, R. (2002). *Cognitive Cooperation for the Sake of the Human-Machine Team Effectiveness*. In: *RTO-HFM Symposium on The Role of Humans in Intelligent and Automated Systems*. Warsaw, Poland. 7-9 October.

5.5 COGNITIVE SYSTEMS ARCHITECTURE – REALISATION ASPECTS

This section is supposed to point out a perspective of how to implement an Artificial Cognitive unit (ACU) on the basis of the proposed theory. Figure 5-28 depicts what has been achieved so far, as a review of the previous sections. The starting point is the human operator as operating element in a work system. In a first

step we model human performance in terms of high level cognitive functions. The analysis of the typical work share in work systems reveals that there are particular shortcomings in terms of these high level cognitive functions on the machine side, namely in the domain of situation understanding and goal-driven behaviour. In order to achieve this capability on the machine side the Cognitive Process is proposed as underlying theory derived from useful findings in cognitive psychology and artificial intelligence research, likewise.

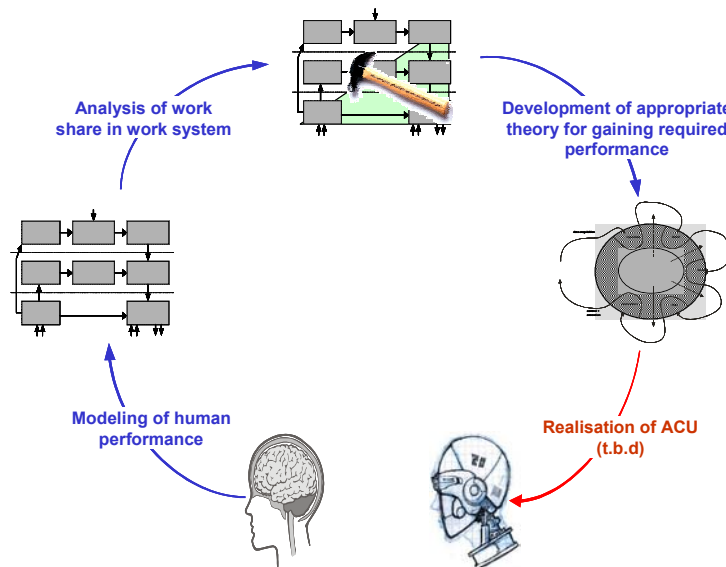


Figure 5-28: Method of Cognitive Systems' Development.

As a next step of the development of a cognitive system according to the approach of cognitive automation, the realisation of an Artificial Cognitive Unit (ACU) has to be accomplished. In the succession of this section an engineering framework for the development of such an ACU will be described: The Cognitive System Architecture (COSA).

COSA offers a framework to implement applications according to the theory of the Cognitive Process. It provides an inference mechanism and various means, which make it possible for the developer of an application to use concepts like 'belief', 'goal' and 'plan' rather than a programming paradigm based on a functional decomposition of an application [1].

COSA is composed of four building blocks (cf. Figure 5-29).

- The kernel implements the theory of the CP and does not contain any application-dependent information. Its only task is to generate behaviour from knowledge. In the current implementation, it is based on SOAR [Laird et al., 1987], which is a general rule-based architecture for developing systems that exhibit intelligent behaviour, as described earlier in this chapter. The CP-Library structures the situational knowledge according to the theory of the Cognitive Process and coordinates the performance of the transformers (interpretation, goal determination, planning, and plan realisation, cf. Figure 5-26).
- The application is formed by several COSA-compliant application components, which correspond to packages (see Figure 5-27). The components provide the a-priori knowledge and may also contain servers with interfaces to the environment or for external calculations.

- The front end provides tools for the developer of an application, which help him to model the knowledge for the application. One part of the front end is CPL (Cognitive Programming Language), which provides a programming support to the implementation of the above-mentioned mental notions 'belief', 'goal', and 'plan' as concepts for knowledge modelling. The CPL code, which represents the knowledge on a rather high abstraction level, is compiled into a code representation understood by the kernel, i.e., SOAR in the current implementation.
- Finally, the distribution layer is responsible for the communication among the modules of COSA. It ensures that components and modules can run on different computers in a network.

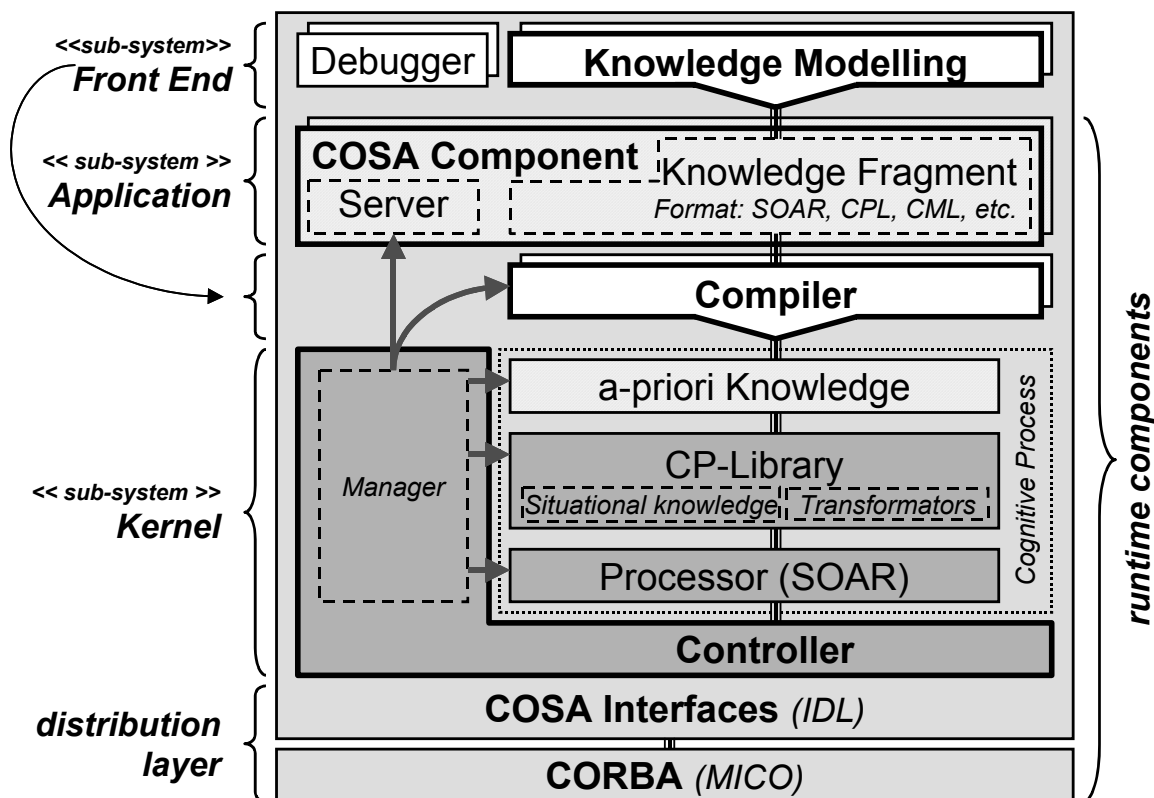


Figure 5-29: COSA – Cognitive System Architecture.

5.5.1 References

- [1] Putzer, H. and Onken, R. (2003). COSA – A Generic Cognitive System Architecture based on a Cognitive Model of Human Behavior. In: International Journal of Cognition Technology and Work.

5.6 APPLIED SYSTEM APPROACHES

The previous sections provided a rather general concept of how to approach artificial cognition and co-operative automation, which represents the current state of the art achieved at the Institute of System Dynamics and Flight Mechanics at the Munich University of the German Armed Forces, at least from a theoretical standpoint. On the practical side this achievement could be attained during the course of several

experimental programmes in the field over the recent 15 years. Most of the works were well documented by multiple publications and internationally well recognised, e.g., [6] reporting the results of the flight trials of the worlds first comprehensive knowledge-based assistant system for flight-deck crews, CASSY (Cockpit Assistant System). In the late nineties followed CAMA (Crew Assistant Military Aircraft) as a prototype system in the military transport domain, e.g., [7] discussing the system architecture, [Schulte & Stütz, 1998] reporting on the successful simulator validation of the system, and [46] pointing out the successful flight tests that followed.

A detailed discussion of the achievements of the working group around Reiner Onken would go beyond the scope of this chapter. Instead of doing that, the rest of this chapter shall be dedicated to a broadening of the view by bringing up three perspectives from other research groups. The first contribution (Sub-section 5.6.1) is provided by Mike Chamberlin (UK) dealing with the issue of Artificial Intelligence from a methods' point of view. This treatment perfectly supplements the findings of Section 5.4, especially of Sub-section 5.4.2, which were pretty much focussed on a unitary approach. Sub-section 5.6.1 will give a nice overview and evaluation of further approaches.

Common to all attempts to computational intelligence of whatsoever kind is the (open) question to the acquisition of the necessary knowledge and it's adequate representation. In Sub-section 5.6.2 Jack Edwards (Canada) tackled the problem of intelligent, adaptive help system design mainly under the consideration a knowledge design and engineering methodology that combines elements of the CommonKADS and IDEF methods, Explicit Models Design and Perceptual Control Theory.

Finally, Sub-section 5.6.3 by Mike Waters and Robert Taylor (UK) opens the perspective for the domain of unmanned underwater vehicles as an application domain. Their model of autonomous decision making renews the idea of cognitive automation from a different perspective, rounding out the picture.

5.6.1 Artificial Intelligence (AI) Methods Perspective

In order for unmanned air vehicles to fulfil their envisaged enhanced roles in the future integrated battlespace, there is an unprecedented requirement for flexible and autonomous operation, representing a massive leap in capability compared to that of today's systems.

This section critically examines the notions of automation and autonomy on UAV and UCAV platforms, and operator decision support; in the contexts of current and envisaged platforms, roles, responsibilities and missions. The relative merits and maturity of AI techniques and technologies are studied and their applicability to providing elements of autonomous behaviour in UAVs and UCAVs are considered in light of these; illustrating how semi- and fully-autonomous UAVs, and operator decision support, can boost flexibility, survivability and mission effectiveness of UAVs/UCAVs, augmenting and enhancing the capabilities of the future warfighter.

5.6.1.1 Introduction to AI Methods

It has long been recognised, and more recently demonstrated through deployments in the Gulf, Bosnia and Afghanistan, that UAVs have significant potential to enhance a force's ability to project combat power. Their range, persistence, altitude and potential for cost and manpower savings make UAVs an ideal candidate for the dull, dirty and dangerous missions of the future; augmenting, replacing or even surpassing the capabilities of manned aircraft.

Removing the human from the aircraft's cockpit enables more efficient and cost-effective platform designs, albeit with the trade off that the operator is now further separated from the action, with a commensurate possibility for loss of situational awareness. With the operator's role needing to evolve from a piloting to a supervisory capacity, treating many UAVs as one system in order to achieve mission objectives, there are serious implications for cognitive workload [1].

5.6.1.2 UAV/UCAV Autonomy Requirements

Small-scale UAVs such as Micro-UAVs (MAVs), are intended to be deployed by ground forces for short-range surveillance. As such, MAVs are supposed to be man-portable and expendable, hence a fully-autonomous architecture is not required. Much larger UCAV/UAV platforms, although originally intended to be expendable, cannot afford this luxury as development and operating costs continue to spiral upwards. With the human operator removed from the vehicle and reduced to a supervisory role, rather than being in full control, a significant automatic and autonomous element needs to be present for the UCAV to achieve any level of survivability and capability at all above that of a cruise missile.

For a UCAV platform to be successful, it has to rely on achievable technologies, and interactions between component technologies must be carefully managed. Development is concerned with trade-offs between platform properties: individual components are themselves sufficiently advanced already. Constructing the airframe is relatively straightforward; achieving desired levels of survivability and mission effectiveness are the major challenges [2]. How processes are integrated with the platform and infrastructures (e.g., datalinks) is the key.

Currently, UAVs such as X-45A are capable of taking off and landing automatically, and following waypoints to a target. They can relay surveillance data to a controller for target acquisition and designation, and deploy ordnance to destroy a soft target.

The main types of mission that are likely to be undertaken by a UAV or UCAV are listed in Table 5-1 [3]:

Table 5-1: Likely UAV or UCAV Mission Types

SEAD (Suppression of Enemy Air Defences)	Attacking air defences, e.g., SAM sites; plus escort and sweep roles
Strike	Attacking pre-defined targets; plus escort and sweep roles
TCT (Time Critical Targeting)	Attacking targets within a narrow window of opportunity; may involve long loitering times
Maritime specific	AEW, ASW, AsuW tasks; organic to naval vessel or task group
ISTAR (Intelligence, Surveillance, Target Acquisition and Reconnaissance)	Functional requirements including, e.g.: Battlefield Surveillance and Reconnaissance; Target Detection, Location and Identification; BDI/BDA
Communications Relay	Extend LOS communications, e.g., UHF, Link 16

ARTIFICIAL COGNITION AND CO-OPERATIVE AUTOMATION

An autonomous UAV/UCAV would have to undertake some of the following actions during each sortie:

- System monitoring.
- Airmanship tasks, e.g., fuel states, aircraft safety.
- Health monitoring/diagnostics, leading to mission re-planning:
 - Work within battlespace infrastructure, i.e., datalinks, communications (manage these); and
 - Fault and damage tolerant control of the aircraft, i.e., it has to fly safely and predictably, work around minor faults, and carry out appropriate procedures in the event of major failures.
- Takeoff:
 - Interoperability with ATC commands, and normal aircraft handling patterns and procedures is vital, even more so for UCAV-N operating from an aircraft carrier (even down to the envisaged level of the air vehicle responding to voice commands from ATC).
- Formation:
 - A need to operate with other manned and unmanned aircraft, in normal airspace, and as part of a package.
- Ingress / Routing to target:
 - Route to pre-defined target;
 - Comply with airspace regulations; and
 - Avoid known and pop-up threats, dynamically altering flight or even mission plans if necessary with SA gained through maintenance of RASP.
- Carry out mission:
 - Compliance with Air Tasking Orders (ATO), SPINS;
 - ROE, Laws of Armed Conflict;
 - Detect, Identify and Acquire Targets- a real-time process for TCT;
 - Weapons release (SEAD, Strike, TCT); and
 - Battle Damage Investigation / Assessment.
- Egress:
 - As ingress; and
 - Added complications for Strike, SEAD, i.e., package re-formation and delousing.
- Landing:
 - Interoperate with airbase landing/recovery patterns and procedures.

5.6.1.3 Applicability of AI Techniques to Mission Requirements

Various AI methods were examined in order to determine their relative merits and particular 'skills', when applied to the types of activity necessary for the autonomous mission tasks identified above (see Table 5-2).

Table 5-2: Relative Merits of AI Techniques when Applied to UAV Mission Management Tasks

	Fuzzy Systems	GAs	KBS	NN	CBR	Hybrid systems	MPS ¹
Scheduling/planning	M	M	M	M	Y	Y	Y
Decision support	Y	N	Y	N	M	Y	
Diagnostics	Y	N	Y	M	Y	Y	
Risk analysis	Y	Y	M	Y	Y	Y	
Data analysis	M	Y	M	Y	M	Y	
Monitoring	Y	N	Y	Y	M	Y	
Optimisation	M	M	N	Y	N	Y	
Interpretation	Y	N	Y	M	M	Y	
Classification	Y	M	Y	Y	M	Y	
Control of systems	Y	M	N	Y	N	Y	

¹ Mission Planning Systems.

Legend	
Y	Yes – highly applicable
M	Maybe – slightly applicable
N	No – inapplicable

The following table (Table 5-3) compares the relative merits of these AI techniques to the mission tasks above, giving the tasks fully autonomous UAV or UCAV would have to undertake, and which AI method, or combination of methods would best be suited. These are then linked to various processes (outlined in Section 4 below, and see [4] for more details) forming an example UAV/UCAV architecture (based on the Sharp control and decisional architecture for autonomous vehicles [5]). The result is the identification of which technique or combination of techniques is best suited to each process.

ARTIFICIAL COGNITION AND CO-OPERATIVE AUTOMATION

Table 5-3: Recommended AI Techniques for Identified UAV Autonomy Requirements, and Mapping to Processes

Action	Capability	Mission Type	AI task for Autonomous UCAV	AI Technique	Process
Autonomous Navigation	Routing to pre-defined target	All	Route/Mission Planning, Risk Analysis, Optimisation	MPS	Route Planner
	Route re-planning		Mission Planning	MPS	Route Planner
	Mission re-planning		Mission Planning	Hybrid (KBS & MPS)	Mission Manager
Surveillance	RASP from own sensor / datalink → SA	All	Monitoring, Interpretation, Classification, Data Analysis, Optimisation	KBS	Situational Awareness, Mission Manager
	Mission/payload sensor management		Scheduling, Control, Data Analysis	Fuzzy	Mission Manager, Situational Awareness
Threat avoidance	Threat Detection	All	Monitoring, Interpretation, Classification, Risk Analysis	KBS	Mission Manager
	Threat Identification			KBS	Mission Manager
	Threat avoidance through Route/Mission re-planning		Control, Route/Mission Planning	Hybrid (KBS / Fuzzy & MPS)	Mission Manager, Route Planner
Destructive	Target Detection	SEAD, Strike, TCT	Monitoring, Interpretation, Classification, Risk Analysis	KBS	Mission Manager
	Real-time Target Identification		Classification, Data Analysis	Hybrid (KBS / Fuzzy & NN)	Mission Manager
	Target Acquisition		Classification	Hybrid (KBS / Fuzzy & NN)	Mission Manager
	Weapons release		Control	NN	Mission Manager, Flight Management
	Battle Damage Assessment		Interpretation, Classification	Hybrid (KBS / Fuzzy & NN)	Mission Manager
Interoperability	Communications to command centre (maintain datalinks, etc.)	All, esp. Comms Relay, ISTAR, TCT	Data Analysis, Monitoring	Hybrid (NN & Fuzzy)	Mission Manager, Situational Awareness
	Integration into battlespace infrastructure		Data Analysis	KBS	Mission Manager, Situational Awareness
	Fly as part of a package	SEAD, Strike	Optimisation, Control, Risk Analysis	Hybrid (KBS / Fuzzy & NN)	Mission Manager, Situational Awareness, Flight Management
	Interoperate with Airbase / carrier patterns and procedures, ATC	All, esp. Maritime	Control, Planning, Interpretation, Data Analysis	Hybrid (KBS / Fuzzy & NN)	Mission Manager, Flight Management, Situational Awareness
	Interoperate with other manned/unmanned platforms	All	Control	Hybrid (KBS & NN)	Mission Manager, Flight Management, Situational Awareness
System	Fault/damage tolerant control, i.e., flight	All	Control, Risk Analysis, Data Analysis, Diagnostics	Hybrid (NN & Fuzzy)	Flight Management
	Health Monitoring/diagnostics		Monitoring, Classification, Diagnostics	CBR	Health Monitor
	D/NAW capability (aircraft & sensors)	ISTAR	Interpretation (sensor data)	NN	Flight Management, Situational Awareness
	Airmanship, e.g., fuel states	All	Monitoring, Diagnostics	KBS, CBR	Airmanship
	Safety & Emergency procedures		Monitoring, Risk Analysis, Control	KBS	Airmanship

5.6.1.4 Recommended Applications of AI Methods

The analysis in Table 5-3 shows that no single AI technique is appropriate for all areas of autonomous operation. The requirements for all tasks are so diverse that one method cannot be a panacea. A hybrid system would offer the best solution, so that a particular technique that excels in one area can be applied to one subsystem, providing input into other subsystems functioning through one or more different techniques.

By comparing the techniques suited to each task (which were outlined in the section above), and the process that contains each task, it becomes apparent (in Table 5-2) which technique, or combination of techniques is most suited to each process (see Figure 5-30 for a diagrammatic representation).

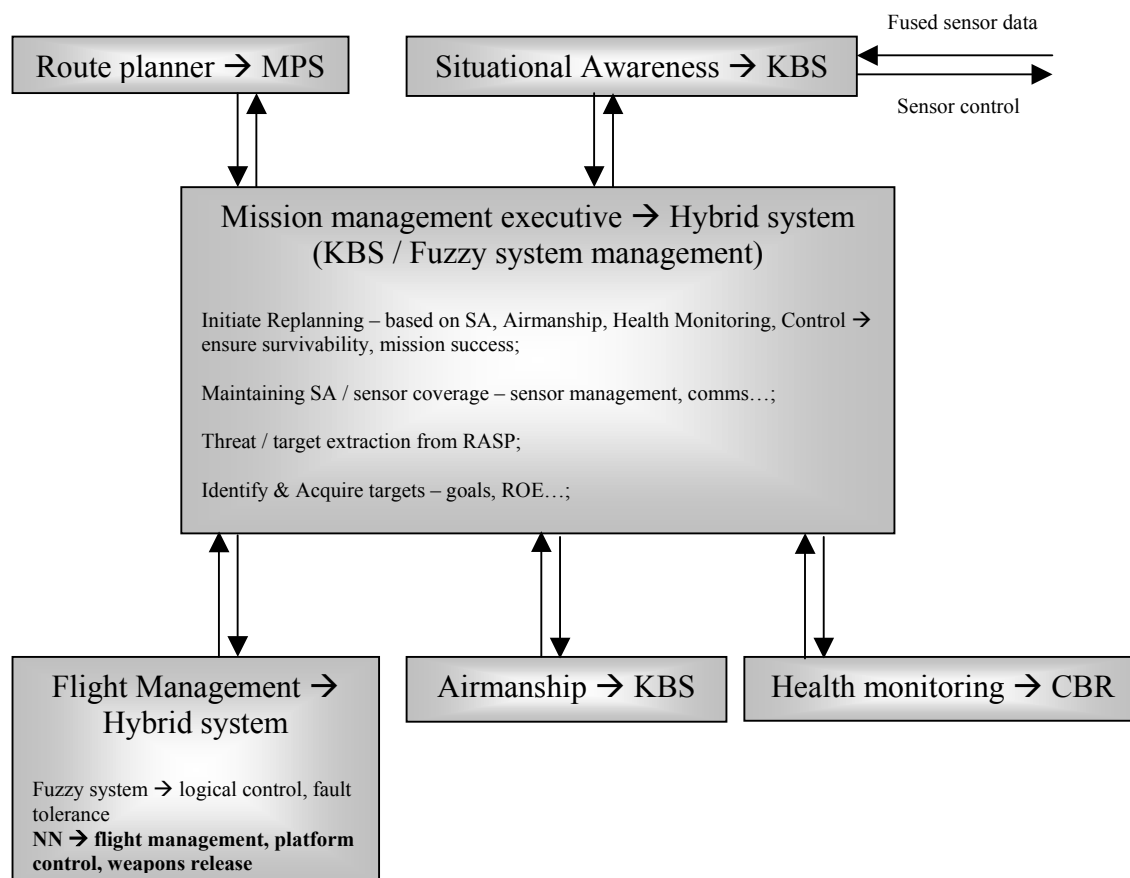


Figure 5-30: Recommended Applications of AI Method.

The **Flight Management** process would be best as a *hybrid* system. A neural network could control the actual platform's flight characteristics, managed by a fuzzy controller receiving instructions from the Mission Manager. This might include neural network for machine vision purposes when the aircraft is operating on the ground (e.g., taxiing around obstacles).

A Case-Based Reasoning system should manage the Health Monitoring process. The present state of the platform would be compared to cases representing nominal operation, and differences used to diagnose failures, and possible remedies, in real time, from a case library.

The Airmanship process would be a Knowledge Based System. This would continually monitor the state of fuel levels, weapons and sensors, and the position of the aircraft with respect to flight levels, safe altitudes, airspace restrictions and so on, advising the mission manager if plans are feasible given current fuel levels, or require re-planning.

Situational Awareness would be provided by another knowledge-based system. This would build a RASP from correlation and fused sensor, datalink, and other information, abstracting tracks, and advising the mission manager on potential threats and targets.

A mission planning system would be best for the Route Planning process. The route planner would take the current mission objective and abstracted RASP from the mission manager and; with knowledge of airspace regulations, the platform's capabilities (from airmanship and health monitoring processes), knowledge of the terrain for masking purposes, and ROE; produce a flight plan.

The Mission Manager is in overall control of the aircraft. This would be use a hybrid technique with inputs from all the other processes feeding a KBS or fuzzy system. A fuzzy system could cope better with uncertain information, however this might be undesirable if information is too vague. The mission manager abstracts information from the SA process into targets and threats, based on mission objectives, ROE and other pertinent information, for the route planner, and passes resulting flight plans to the control process. Any changes to the environment, ROE, mission objectives, or RASP may result in re-planning the mission, as could advice from the airmanship or health monitoring processes.

It is important to remember also that a human will still be in the loop somewhere, most likely monitoring the UAV/UCAV as part of a system of systems from a ground station, and possibly taking tactical decisions about the overall mission plan. A soldier on the ground may request surveillance imagery, or even Close Air Support. The overall requirement is for flexibility and network-enabledness as part of the future integrated battlespace.

5.6.1.5 Conclusions on AI Methods

This section has examined the spectrum of available UAV platforms and underpinning technologies in the context of potential scenarios in order to discuss the relative merits of different AI techniques to improve mission effectiveness.

Of necessity, at this period, most effort has been expended in platform configuration and power plants with bandwidth limitations initially appearing as the first barrier to more widespread application, after the need for greater systems integration.

A trade off then emerges of bandwidth requirements for transmission against onboard processing for greater autonomy, and so reducing reliance on transmitted data.

Autonomy is often seen as a panacea to address the bandwidth problem with AI techniques in the vanguard for achieving this state, although reference to the maturity of different AI techniques quickly refocuses attention on candidate approaches for down selection for any practical demonstrator.

Autonomy and automation are not synonymous, and examples are offered in the report that illustrate the salient differences and the associated impact on elements of any system.

Tabulation of the strengths and weaknesses of different AI techniques indicate the potential application area to best exploit the relevant merits and maturity levels of each technique.

Contrary to widespread beliefs held by non-specialists, this study indicated only limited potential for neural networks, genetic algorithms and fuzzy systems in UAVs, except as a component of more comprehensive hybrid solutions. Fuzzy systems and neural networks were seen as predominantly of use in control and classification applications.

Knowledge-based systems were seen as essential for monitoring, interpretation and data analysis, that is, the less autonomous aspects of missions such as diagnostics and decision support.

The application of specific AI techniques was found to be largely dependent on the level of autonomy envisaged. Higher levels of autonomy suggested more hybrid systems to exploit the complementary capabilities of different AI technologies.

From the systematic consideration of the relative merits of different AI approaches for each UCAV mission requirement, it became possible to identify which AI technique, or combination of techniques are best suited to each element of the system.

Conversely, if different or varying levels of autonomy are considered, appropriate AI techniques can be identified and recommended to satisfy separate elements of the UCAV/UAV system.

5.6.1.6 Recommendations on AI Methods

This study has outlined the relevance and maturity of AI techniques and technologies to address the issue of autonomy in future UAVs and UCAVs. As a result of the process of breaking down missions and roles to address the required functionality it became evident that no single technique was a panacea for complete platform autonomy, however certain methods can be applied to particular areas, which might be self-contained should the goal of complete autonomy be judged unobtainable or undesirable.

The most attainable solution would involve a complex hybrid architecture, utilising several methods to address particular areas, in self-contained elements or as a coherent whole. If a fully or even partially autonomous air vehicle is the goal, then much further development will be required to refine potential architectures in light of implementation issues.

On- and off-board diagnostics and health monitoring could be achieved by a case-based reasoner. A knowledge-based system could address airmanship tasks. Autonomous flight management might be accomplished with a hybrid system comprised of a controlling fuzzy system fed by a neural network. A knowledge-based system is applicable to managing situational awareness, with dynamic route planning an re-planning undertaken by a mission planning system.

Finally, a hybrid system could form the mission management executive, based on a KBS or fuzzy expert system, fed by inputs from the other elements.

There is a vital need to consider more closely the actual architecture of a proposed fully-autonomous UAV in order to gain a better understanding of the particular systems that are likely to be implemented. Then, and only then can a deeper look can be taken at which AI techniques are most applicable to each subsystem; this report identifies the areas that best suit the relative 'skills' of certain AI methods.

Any realistic recommendation would be time and funding dependent. Shorter timescales and minimal funding suggest applications limited to diagnostic advisors, whilst longer timescales and more generous funding make possible hybrid AI solutions for applications requiring full autonomy.

AI techniques could also be more confidently employed in areas where less capability is required. This report has identified some of the many issues influencing the path to full autonomy, demonstrating the magnitude and complexity of the obstacles to be overcome. An interim solution could employ intelligent tools to aid the operators of UAVs and UCAVs, both ground and air controlled, to enable them to utilise many more vehicles than at present, whilst working in a supervisory battle management role, as opposed to a pilot role. AI technologies employed in operator decision support, and on- and off-board diagnostics systems could go a long way towards meeting these requirements.

5.6.1.7 References

- [1] Draper, M. (2002). Minutes of the first meeting of NATO RTO Task Group HFM-078/TG-017 “Unmanned Military Vehicles – Human Factors Augmenting the Force”. Salisbury, UK, 7th – 9th May.
- [2] Stolz, S., Capt. UA Air Force UCAV Concept of Operation. Presented at IQPC UCAV Conference, London: 21st – 22nd October.
- [3] Nolan II, R.C., Maj; USAF. (1997). The pilotless Air Force? A look at replacing human operators with advanced technology. Air command and Staff College, AU/ACSC/0530/97-03.
- [4] Chamberlin, M.R., Thomas, M.J. and Hope, T.M.H. (2003). Assessment of the potential for application of AI techniques to UCAV mission management. QinetiQ Report: QINETIQ/FST/TWP031151. March. UK Restricted.
- [5] Vlacic, L., Parent, M. and Harashima, F. (2001). Intelligent vehicle technologies: theory and applications. Butterworth Heinemann.
- [6] Prévôt, T., Gerlach, M., Ruckdeschel, W., Wittig, T. and Onken, R. (1995). Evaluation of intelligent on-board pilot assistance in in-flight field trials. In: 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems. Massachusetts Institute of Technology, Cambridge, MA. June.
- [7] Walsdorf, A., Onken, R., Eibl, H., Helmke, H., Suikat, R. and Schulte, A. (1997). The Crew Assistant Military Aircraft (CAMA). In: The Human-Electronic Crew: The Right Stuff? 4th Joint GAF/RAF/USAF Workshop on Human-Computer Teamwork. Kreuth, GE. September.

5.6.2 Intelligent, Adaptive Help System Design

This contribution describes a comprehensive approach to developing decision support systems for providing intelligent, adaptive aiding to users. The approach is guided by the use of a knowledge design and engineering methodology that combines elements of the CommonKADS and IDEF methods, Explicit Models Design and Perceptual Control Theory. The following sections describe how those individual components should be used in constructing an intelligent help system.

5.6.2.1 The CommonKADS Methodology

“Intelligent” software, such as that required for a truly adaptive help system, is built using knowledge-based systems (KBS), which imitate human reasoning. Such systems are typically composed of formal representations of knowledge about a particular domain and a mechanism that enables the system to “reason” about that knowledge through the application of inferences. This section examines the CommonKADS management and engineering methodology for analysing and designing knowledge-based systems and the role of that approach in developing help systems.

The CommonKADS methodology provides a step-by-step approach to analysing a given problem domain. Questions are posed at each stage through standard “worksheets,” which provide a systematic tool for documenting both questions and answers concerning key issues. Individual, numbered guidelines are also offered to assist with the construction of more detailed components of the models.

5.6.2.2 Application of CommonKADS to Help System Design

The process of applying CommonKADS to build a help system involves the specification of the following six models:

- Organisation Model;
- Task Model;
- Agent Model;
- Knowledge Model;
- Communication Model; and
- Design Model.

5.6.2.2.1 Organisation Model

The Organisation Model is assembled during the initial feasibility and assessment phase of a CommonKADS analysis. The primary emphasis of that phase is to examine organisational or business processes that could benefit from the implementation of a knowledge system. Coupled with that is the subsequent feasibility analysis that weighs the costs associated with such an implementation against the projected benefits. Thus, a system must be sufficiently knowledge-intensive to warrant its implementation using CommonKADS. Worksheet questions help to identify the structure of the organisation, relevant processes, people and resources involved and knowledge assets required.

It should be noted that the authors of the CommonKADS approach emphasise the importance of an initial phase in which a systematic analysis of the organisation is conducted. This points to situations where applying the methodology has revealed needs for a knowledge system that are substantially different from those projected at the outset of analysis.

5.6.2.2.2 Task Model

The Task Model in CommonKADS is created primarily as part of the organisational analysis and feasibility assessment and focuses on high-level tasks and goals of agents in the system. Tasks should be examined with a view to identifying those that are sufficiently knowledge-intensive and that would benefit from the implementation of a knowledge-based system.

To create an explicit representation, tasks and sub-tasks should be represented using flow diagrams from the Unified Modelling Language (UML). UML has been adopted by the developers of CommonKADS as the standard technique for schematically depicting activity, state and class diagrams that can represent a wide range of concepts such as data flow, inferences and task structures.

Construction of the Task Model involves the creation of a task hierarchy, in which tasks are decomposed into sub-tasks. Questions posed during Task Model creation relate to constituent sub-tasks, the agents and objects involved, the timing of the task and knowledge required for performing it. That information can then be referred to later during knowledge model construction.

Although CommonKADS specifies that UML be used for representing task hierarchies, there are limitations to UML's expressiveness such that a complement to UML be considered in implementing help systems for certain applications. The limitations relate to the representation of temporal constraints, such as concurrency of tasks and their performance in real-time. In designing help systems for applications in which precise timings of events is critical, it is recommended that the IDEF3 language be used for the graphical representation of tasks and sub-tasks (see the "IDEF3" section, below).

A formal statement of tasks and sub-tasks will help to identify responsibilities that can be carried out by software agents. Such tasks include:

- Monitoring the user's activities;
- Inferring the user's immediate goals and higher-order intentions; and
- Generating system plans to assist the user in the most effective way given current circumstances.

Identification of those tasks should be performed in consultation with subject-matter experts.

It should be noted that the creation of a task hierarchy is fundamental to several of the approaches that comprise the integrated methodology, including Explicit Models Design and Perceptual Control Theory. Task hierarchies are discussed further in sections that follow (see the "Explicit Models Design" and "Perceptual Control Theory" sections, below).

5.6.2.2.3 Agent Model

Like the two models already described, the Agent Model is developed during the initial feasibility phase. It is used to identify the participants in the itemised tasks so that their responsibilities can be incorporated into any resulting knowledge system. That process also assists with identifying expert sources of knowledge that can be useful in supplying information and providing rules for the knowledge base.

Construction of the Agent Model involves examining the tasks in which each agent is involved, the other agents with which it communicates and knowledge that is required to complete its tasks.

5.6.2.2.4 Knowledge Model

The Knowledge Model contains a detailed enumeration of all knowledge required by the system to perform its tasks. Thus, most of the architecture of the knowledge system is designed during the formulation of that model.

The Knowledge Model is subdivided into three categories: "domain," "inference" and "task" knowledge. Domain knowledge contains all of the data used by the application, which, in object-oriented terminology,

would correspond to the class definitions and object instances. In the case of a help system, the domain knowledge should include knowledge relating to the capabilities and functions of the software, including user and system tasks described in the Task Model. Domain knowledge should also include information about the external environment, as contained in the EMD World Model (see the “Explicit Models Design” section below).

The second component of the Knowledge Model is the inference knowledge, which is a collection of methods that act on the domain knowledge. CommonKADS provides a catalogue of inference templates, an approach that has multiple advantages. Creating methods that can be applied generally allows them to be reused readily in other applications. Because they have been applied in other situations, they come pre-tested and therefore contribute to the overall reliability of the knowledge system. Examples of inference knowledge in a help system would include methods for inferring goals from actions or hypothesising a plan based on a user’s actions.

The final component of the Knowledge Model is task knowledge, comprising a set of higher-level methods that implement a hierarchy of tasks and sub-tasks. At the lowest level, the sub-tasks make use of methods in the underlying inference knowledge layer, which in turn operate on the domain knowledge. Task knowledge in a help system would include a representation of the full task hierarchy derived in the specification of the EMD Task Model (see the “Explicit Models Design” section below).

As with the inference knowledge, there are templates available for task knowledge and they share the same benefits of reusability and reliability. Templates that are provided include those for planning, scheduling and monitoring, all of which are useful in a help system. Planning and scheduling are tasks required for plan generation and monitoring is essential to plan recognition (see the section on Explicit Models Design below).

Knowledge modelling in any context typically involves the creation of an ontology, and CommonKADS is no exception. Ontologies are formally specified frameworks within which knowledge can be represented. A chief goal in producing an ontology is to identify patterns in the knowledge and exploit those to produce a highly organised and concise specification. One of the main motivations for generating an ontology for a particular domain is to allow its reuse in other applications.

In order to describe fully the Knowledge Model for a help system, it will be necessary first to design the content of the various Explicit Models. The section on “Explicit Models Design” describes how those models are constructed.

5.6.2.2.5 Communication Model

The purpose of the communication model is to describe communication that must occur among agents in the knowledge system. That can include dialogue that is both between the user and system agents, and between individual software agents.

Communication is broken down using a transaction model. For each pair of agents that must interact, a communication plan should be constructed (usually represented using UML) that outlines the flow of information and decisions affecting that flow. That is decomposed further into a detailed itemisation of individual transactions, where each one represents a message sent from one agent to another. Each transaction should be described in terms of the agents involved, the content of the messages and knowledge objects exchanged.

Standard patterns of communication are described in CommonKADS, such as the straightforward “Ask” and the associated “Reply,” or slightly more complex exchanges such as, “Require,” which can have “Agree” or “Reject” as responses. A library is offered for those and other standard modes of communication.

One type of user-system interaction in a help system involves the presentation of information by the system and possible acknowledgement from the user. (In situations where it would be disruptive to the user to provide explicit feedback, the system should infer through indirect means that the user has received the information.) In addition to that system-initiated communication, users should be able to request help information from the system, which necessitates a second form of dialogue. Interaction may also consist of a clarification dialogue between user and system agents whereby the system seeks information when the user’s current intentions are ambiguous, but care must be taken to avoid unnecessary requests for communication with the user. Users may also seek clarification on system goals or activities.

The Communication Model also describes dialogue that occurs among system agents, which is important in the help system to maintain co-ordination among semi-autonomous entities. Agent interaction in the Communication Model is revisited in the “Software Agent Paradigm” section below.

5.6.2.2.6 Design Model

The Design Model examines hardware and software issues related to the construction of the knowledge system. The aim is to take the implementation-independent specifications from the Knowledge and Communication Models and develop a detailed design for constructing the software application, and in the process preserve the structure of those models.

CommonKADS help systems should be designed using the Model-View-Controller (MVC) architecture. In that approach, the Application Model contains the rules, inference functions, and knowledge bases that are responsible for the main functionality of the application. The Views subsystem provides external views of the data in the application model, which can be in the form of a user-interface or can also involve the presentation of information to an external software system. The Controller handles the processing of events, the triggering of tasks and inferences, and the responsibilities of the Communication Model.

The next design step is identifying the target software and hardware platforms. It is recommended that CommonKADS systems be implemented in an object-oriented (O-O) environment.

Some suggested languages for implementing CommonKADS systems are Prolog and Java, but that is not to the exclusion of other possible environments (For examples and source code, see [1] and the CommonKADS web site at www.commonkads.uva.nl).

Once an implementation environment has been selected, the final step in constructing the Design Model is to create a detailed plan for implementation of the Application Model, Views and Controller, as well as the tasks, inferences and domain knowledge within the Knowledge Model. Many details of the plan are dependent on the chosen environment.

CommonKADS also includes guidelines on project management that are designed to accommodate the unique needs associated with knowledge projects.

5.6.2.3 IDEF Standards

The IDEF (ICAM Definition) standards, like the CommonKADS methodology, provide a set of guidelines for analysing processes, activities and information needs within organisations. The IDEF documents are a collection of numbered standards, each of which provides formal guidelines for analysis and design in a particular area. The two standards relevant to help system design are “IDEF3: Process Modelling” and “IDEF5: Ontology Modelling.”

5.6.2.3.1 IDEF3: Process Modelling

The CommonKADS approach uses UML for the schematic representation of processes and associated data, agents, tasks and inferences. One of the drawbacks of UML is that it is inflexible in representing temporal relationships and constraints among those elements. Two important temporal concepts are synchronisation and real-time systems. In the case of the former, a distinction is made between synchronous and asynchronous activities, i.e., those that occur at the same time contrasted with those that do not, respectively. That distinction can have important consequences for the system being modelled, where, for example, tasks that can be carried out synchronously can shorten the total time required to complete a procedure and thereby increase the efficiency of the system. When modelling real-time systems, much more attention must be paid to the precise times at which events occur, not simply their relative occurrence, and that can have direct bearing on whether or not the modelled system will perform as intended.

Unlike UML, IDEF3 permits flexible modelling of temporal concepts. For example, symbolic representations exist for depicting whether multiple activities are synchronous or asynchronous and whether all activities must be complete before the next steps in the process can continue.

Modelling of real-time systems is possible using IDEF3’s elaboration language, which allows symbolic representations of complex constraints that cannot be depicted using the schematic language alone. The language, based on a subset of the Knowledge Interchange Format, permits formal logical representations of process constraints and allows precise specification of event timings and durations.

Because IDEF3 has full flexibility for temporal modelling, and because it has been in use for a long time, IDEF3 is recommended for use in help system development for applications with precise timing needs. In future, it may be possible to achieve greater flexibility for representing temporal constraints using UML. The upcoming release of the language (UML 2.0) promises to offer more of such capabilities, and the addition of the Object Constraint Language (OCL) to UML also features added support for temporal modelling.

5.6.2.3.2 IDEF5: Ontology Modelling.

Another IDEF standard that is relevant to help system design is IDEF5, which, like CommonKADS, provides specifications for ontology modelling. CommonKADS provides techniques for developing ontologies, including guidance on expert knowledge elicitation, formal descriptions of concepts, attributes and relations, and a formal language for representing ontologies. Although those are powerful components, ontology construction is explored in greater depth in IDEF5, with more guidance offered and more examples provided. The IDEF5 approach has five steps:

- Organising and scoping;
- Data collection;
- Data analysis;

- Initial ontology development; and
- Ontology refinement and validation.

The organising and scoping phase examines the context and purpose of the project, and can make use of the material assembled during the specification of the Organisation, Task and Agent Models of CommonKADS. Data collection involves acquiring raw data by, for example, examining existing systems or eliciting knowledge from experts. Data analysis attempts to refine the raw data into a form more usable in an ontology. Initial ontology development creates a draft of the ontology which is further developed in the refinement and validation phase. The methodology divides each of those five stages into sub-steps and provides detailed guidelines on how to accomplish each.

5.6.2.4 Explicit Models Design

Explicit Models Design (EMD) is a development approach that seeks to make explicit the knowledge required by intelligent software systems. The approach compartmentalises software knowledge into five distinct, interacting models:

- Task Model, containing knowledge (beliefs) about tasks being performed;
- System Model, consisting of the system's knowledge (beliefs) about itself and its abilities;
- User Model, comprised of knowledge (beliefs) relating to the user's abilities, needs and preferences;
- World Model, representing knowledge (beliefs) about the world relevant to the purpose of the software; and
- Dialogue Model, containing knowledge (beliefs) related to communication among human and software agents.

Plan recognition and plan generation are two additional processes that operate within the EMD framework to enhance the software's ability to support the user. Plan recognition seeks to establish the current goals of the user in the context of a larger plan. This process also seeks to recognise goals, plans and actions in terms of the help that might be required by a user to perform a task in a more effective way. Plan generation is used by the system to develop strategies to accomplish its goals, which principally involve providing help to the user. Those techniques, and the individual Explicit Models, are described below in the context of the help system.

5.6.2.4.1 EMD's Contributions to the Help System

Within the help system, EMD offers a means of subdividing the content of the CommonKADS Knowledge Model into components, described in the following sections. Specification of all models must be done in consultation with subject-matter experts.

5.6.2.4.2 Task Model

The Task Model contains knowledge relating to the tasks being performed by the user, represented as a hierarchy of actions, goals and plans. At the lowest levels of the hierarchy are primitive interface actions, such as button clicks and menu selections. EMD recognises that each deliberate interface action carried out by a user is in support of a particular goal and that actions may be expressed in the terminology of such goals. For example, if a user clicks an "OK" button, the system can infer that the user's goal was, "to click the 'OK' button." While the system can easily infer that low-level goal from the simple act of clicking an OK button,

it is typically much more difficult to establish a higher-level purpose unless additional actions are observed. That process, which involves both higher-level goals and context (the particular “OK” button that was clicked), is described in the “Plan Recognition” section below.

Above the primitive actions and their associated low-level goals in the hierarchy are higher-level goals, which can be achieved only by satisfying one or more primitive goals. Sufficiently high-level goals are often associated with what are commonly known as tasks.

A path from a terminal node of the tree up to a higher-level goal constitutes a plan for accomplishing that goal, and there can be many possible plans for satisfying a given high-level goal. Plan recognition enables the system to determine which of those plans a user is pursuing (see “Plan Recognition” below) and plan generation (see the “Plan Generation” section) permits the system to select a course of action from its available plans, or to recommend a series of actions for the user to satisfy an inferred high-level goal.

The tracking of user interface actions and inference of associated goals provides the system with a basis for understanding what a user is trying to accomplish and for helping that user in ways that are both relevant and useful. The system’s ability to deduce user goals would be an essential part of any intelligent help system and EMD provides effective methods for designing such a system.

5.6.2.4.3 System Model

The System Model is composed of the system’s knowledge about itself, its abilities and the means by which it can assist users. Like the Task Model, the System Model also contains a goal hierarchy, describing the tasks, goals and plans that the system can carry out in support of the user. Those goals are characterised as system support goals.

In the help system, the System Model task hierarchy includes high-level goals, such as, “to assist the user,” which would be decomposed into sub-goals, such as those associated with assuming control of functions it had been assigned, monitoring system status and helping the user to complete his or her tasks.

5.6.2.4.4 User Model

The User Model is comprised of knowledge about the user’s abilities, needs and preferences. That information is obtained in three ways:

- From information volunteered by the user;
- From results of system requests of the user; and
- From system monitoring of user’s activities.

It is worth noting that the system should be able to identify a user so that it can maintain a unique profile for each user. Unless that can be done, the system is reduced to providing information that is often too general, repetitive or useless.

Information volunteered by a user often occurs in the context of specifying options and preferences to the system. It is important that users be able to specify preferences in order to facilitate efficient use of the software, and that is especially useful in applications that offer a large number of features and settings. One method of providing that flexibility is through the establishment of agreements between the user and system using the PACT approach (see “The PACT Approach and Automation Levels” section, below).

There are several ways in which systems can construct user models by explicitly asking questions of a user. For example, if the system has determined which task a user is pursuing, it could enquire whether assistance is needed in carrying out that task. The system also might ask if the user is aware of more efficient plans for accomplishing the task. Finally, if the system cannot determine a user's current plan, it may seek clarification on the user's intentions.

In a truly intelligent system, User Model knowledge is acquired indirectly by monitoring user activities in a Task Model. If the system observes the user carrying out significant and logical portions of a particular plan, it assumes with a fairly high degree of confidence that the user understands that process. The system's confidence increases as the user is observed to repeat the procedure.

If the system determines there is a high probability that a user lacks certain required knowledge, it could signal a need to offer the information. The system must be able to gauge the importance of communicating the information in order to establish a method for doing so. For example, if elements of the total system are at risk of being lost, the user likely would need to be informed immediately. In contrast, advice on carrying out tasks efficiently might not be presented until the user has either completed the current task or finished the session.

5.6.2.4.5 World Model

The World Model contains the software's knowledge about the external world: the objects that exist in the world, their properties and the rules that govern them. Those rules can take on a wide variety of forms, such as physical (e.g., the physical properties of objects in a workspace) and psychological (e.g., rules describing human behaviour in situations of high cognitive workload).

The process of knowledge elicitation required to construct a World Model involves creating a formal representation of information gleaned from subject-matter experts. The resulting compendium of domain-specific knowledge often includes useful information that experts have learned through experience is not contained in existing standard operating procedures. That knowledge can then act as feedback in the review of those procedures.

Knowledge stored in the World Model will form the basis of tutorials and "wizards" guiding the user's pursuit of goals. That guidance may include providing recommendations on creating and manipulating objects, as well as accessing and entering data, activities that frequently require an understanding of how elements within the software interrelate with those in the external world. That knowledge will be structured to support wizards that are adaptable to the range of domains for which help is to be offered.

5.6.2.4.6 Dialogue Model

The Dialogue Model contains knowledge about the manner in which communication takes place among user and system agents. Such communication would involve interaction between the user and system and among other system agents.

Because there are many system agents in a help system, it is essential to specify a common language and protocol for them to communicate. In addition to that, effective user-system and system-system collaboration will require the explicit representations of communication provided by the Dialogue Model.

5.6.2.5 Plan Recognition

The ability to recognise user plans is an important element in EMD and enhances the system's "awareness" of what a user is trying to accomplish so that it can decide how best to offer assistance. It is the infrastructure of

intelligent, adaptive aiding. The COLLAGEN plan recognition approach is recommended for help system implementation.

COLLAGEN uses a “recipe” approach whereby plans that the user may be pursuing are assembled from plan fragments. When an interface action is observed by the system, the fragments are assembled to form alternate sets of plans that might explain why the user performed that action. There may be many possible sets. As further user actions are observed, the number of possible sets that encompass that series of actions diminishes, leading to a more accurate determination of the user’s true plan.

Plan recognition should occur in the context of a system of rules to classify user activities according to a set of criteria that identify whether the user is carrying out the current task:

- Correctly;
- Completely;
- Consistently;
- Efficiently; and
- Safely.

Violations of those criteria should signal a possible opportunity for the system to help the user (See “The Five-Part Taxonomy for Plan Recognition” section, below).

5.6.2.5.1 Plan Generation

Plan generation is the process by which the system develops strategies for accomplishing its goals to assist the user. It is based on System Model knowledge of a hierarchy of available support goals and plans, Task Model knowledge of the user’s current goals and plans and User Model knowledge of the operator’s preferences and abilities.

Plan generation in the help system would seek to construct the most effective plans for offering help to the user, e.g., by displaying a help message immediately or by waiting until a suitable time to present the information with less disruption to the user. System generation of plans also will depend on the selected level of automation.

The processes of plan recognition and plan generation also can be associated with activities in Perceptual Control Theory (PCT), whereby plan recognition is associated with the perceptual input to hierarchies of system control loops and plan generation forms the behavioural output of similar hierarchies. Those parallels bridge the EMD and PCT techniques in the help system (see the “Perceptual Control Theory” section below).

5.6.2.6 Feedback

The concept of feedback is important in EMD for establishing mutual understanding and support between the user and the system, enabling one agent to inform another of its goals, plans and knowledge. Feedback can assume multiple forms, both explicit and subtle.

Explicit feedback can occur in the form of dialogues among agents. For example, the system may ask a user whether he or she is familiar with a particular concept. The user’s response constitutes feedback to the system, providing knowledge for the User Model and therefore enabling the system to offer more appropriate

assistance. Similarly, a user might ask the system to explain its last action, particularly if that action was performed on the system's own initiative. The response from the system is feedback that gives the user a better understanding of how the software operates. The communication of explicit feedback among agents is governed by the Dialogue Model, which must be designed to support exchanges among agents involving the provision of feedback.

A less overt form of feedback arises in the form of system support goals and user goals. For example, if a user's goal is to open a window in the software interface, the system will have a corresponding support goal to display that window. The display of that window constitutes feedback to the user that the goal of opening the window in the virtual environment has been achieved. Representations of user goals also are important forms of feedback since they are the primary means by which the system knows and learns about a user. Detecting user goals is detecting feedback in that those goals implicitly inform the system of a user's plans, abilities and preferences.

5.6.2.7 Perceptual Control Theory

Another theoretical approach recommended for use in help system design is Perceptual Control Theory (PCT). IDEF and CommonKADS methodologies provide frameworks for approaching the design and implementation of the system. PCT and Explicit Models Design (EMD) have the potential to influence how the system functions within that implementation framework. This includes how it determines the goals a user is trying to achieve, the plans for achieving those goals and how it can assist the operator most effectively. The techniques complement one another and together provide an opportunity to form a comprehensive approach that combines the strengths of the individual components.

PCT is founded on notions from control theory, in which closed-loop, negative-gain, feedback systems can be used to build powerful models of goal-directed behaviour and to implement complex systems. The ways in which PCT contributes to help system design fall into two basic categories:

- Performing hierarchical goal analyses; and
- Using PCT principles in the algorithms of the system.

5.6.2.7.1 Hierarchical Goal Analysis of Help System Tasks

A method has been proposed for Hierarchical Goal Analysis (HGA) using principles from PCT, and that technique has the potential to produce a robust and complete task and goal decomposition for help system implementation. That approach to systems analysis examines the goal of an agent as a desire to achieve a certain perception.

The PCT-based HGA technique permits two additional analyses to be performed. The first is a stability analysis that identifies possible conflicts among multiple human and machine agents acting on the same system. The second is an analysis of information flow up the hierarchy, which can influence feedback in the system, affecting error-correction at higher levels. Traditional HGA systems analysis techniques consider only the downward flow of information in the hierarchy. In the case of a help system, it is important that information in the form of system and user goals and sub-goals be able to flow freely in both directions. Stability and information flow analyses could contribute to the generation of a robust goal hierarchy for the help system.

A parallel can be drawn with the flow of information within the action, goal and plan hierarchy of Explicit Models Design. When a user is performing actions in the interface, there is a downward flow of information

to which the system responds with system support goals that feed back upward. From the point of view of the system, its goals are met with feedback from the user flowing in the opposite direction. Those properties make the PCT-based HGA approach equally applicable to a parallel analysis within the EMD hierarchies.

5.6.2.7.2 Control Loop Hierarchies

PCT systems can be implemented as a hierarchy of control loops, wherein the output of the higher levels determines the reference signals at the levels below and the perceptions at lower levels feed the inputs at the levels above.

To implement control loops in the help system, the loops need to be assigned a hierarchy of goals, modelled largely at that level and described in the “Hierarchical Goal Analysis of Tasks in the Help System” section above. Those control loops have as input the actions carried out by the user. The actions serve as a basis for system perceptions about the user’s need for assistance and that constitutes feedback in the loops.

5.6.2.8 Help System Goals and Sub-Goals

If a high-level goal of the system is, “to have the perception (to believe) that the user is performing the current task sufficiently well, that is, in a way that requires no intervention by the system, a control loop would need to be monitoring activities at the interface (perceptual input) to detect the satisfaction of that goal. Support for such a control loop means that the system must infer and represent a belief that the user is engaged in a particular task based on perceived user activity at the interface. In order to infer such a belief, the system must have knowledge of the structure of goals and sub-goals necessary for operators to perform the task.

The high-level system goal can be further decomposed into sub-goals concerning types of user activity that would suggest to the system whether some form of assistance is necessary. System control loops would identify a need to offer help when it is perceived that the user is not performing a task:

- Correctly;
- Completely;
- Consistently;
- Efficiently; and
- Safely.

That gives rise to five sub-goals, each with its own hierarchy of sub-goals. The system’s decision to offer help is based in part on an assessment of user needs according to whether tasks are being carried out in compliance with the five criteria above. For more detail, see the section on “The Five-Part Taxonomy.”

In an adaptive interface, system-generated plans to assist users should be incorporated into the behavioural components of control loops. Plan generation mechanisms should examine perceptual error signals and formulate appropriate behavioural responses to correct them. The plan generator should take into account the magnitude of the error signal in determining the optimal behaviour for providing assistance under the circumstances, whether it be automatic or involve querying the operator on how to proceed.

5.6.2.9 Software Agent Paradigm

An autonomous software agent is a programme with the ability to sense its environment and to act on that environment over time to achieve some purpose and to influence what it will sense in the future. Further

distinctions among agents can be made based on their behaviour, for example, communicative agents can interact with other agents or people; adaptive (or learning) agents can alter their behaviour based on past experience; and, mobile agents can move themselves to other machines.

The agent-oriented development paradigm offers several advantages that were not addressed by earlier object-oriented approaches, including:

- Increased modularity;
- Enhanced reusability;
- Improved organisational effectiveness;
- Increased speed;
- Increased reliability; and
- Better distribution.

5.6.2.9.1 Agents in CommonKADS

The CommonKADS (CK) methodology is entirely consistent with the use of software agents. The Agent Model in the methodology allows for systems with multiple human and software components.

(See “The CommonKADS Methodology” section, above)

A Multi-Agent System extension of the CommonKADS methodology (MAS-CommonKADS) has been proposed and is recommended for use in help system development. The methodology was developed to add specific agent-related constructs, including those associated with:

- a) Inter-agent communication;
- b) The division of tasks among individual agents; and
- c) The implications for implementation of multi-agent systems.

The Communication Model in CommonKADS is primarily focussed on interaction between the user and individual system agents, with little attention paid to communication among the system agents themselves. To address that issue, MAS-CommonKADS incorporates a Co-ordination Model, which specifies how messages are exchanged, what communication protocols are used and what abilities each agent has for interacting with others. Because of the many commonalities between the Communication and Co-ordination Models, the latter should be treated as an entity within the former.

The division of labour, allocated tasks, among agents is an important consideration in the MAS-CommonKADS approach. The physical locations of agents and connections among them can influence the assignment of responsibilities to each component. Task allocation also affects the knowledge requirements of each agent.

The multi-agent approach further influences the construction of Design Model specifications. Consideration must be given to network facilities and transfer protocols according to hardware and software constraints.

5.6.2.9.2 Agents in Explicit Models Design

Explicit Models Design (EMD), described above, also supports multi-agent system development. EMD recognises the roles of the User and System as agents and can accommodate both multiple human users and system agents, each represented by its own User or System (Agent) Model.

The EMD Dialogue Model provides a framework for describing communication among multiple human and system software agents. That model allows for various modes of communication, including the following, relevant to the help system:

- A system providing help information and requesting acknowledgement from a user;
- A system prompting a user for clarification feedback about that user's goals; and
- A multi-agent system communicating internally to co-ordinate its overall activity.

As indicated earlier, the System Model in EMD represents the system as a set of co-operating autonomous agents. Provisions are also made for external agents to play a role supporting the goals of both human users and system agents.

5.6.2.10 Hierarchical Goal Analysis (HGA) of Tasks in the Help System

Hierarchical goal analysis (see above, Section 5.4 Perceptual Control Theory, for a discussion of HGA) can be applied to the task goal hierarchy for the help system. In the same way, HGA can also be used in an analysis and design of a goal hierarchy for a network of intelligent agents to assist human users. That analysis offers the same benefits described earlier: a thorough decomposition of the goal-plan-action hierarchy along with stability and information flow analyses.

The highest-level agent network goal could take the general form: "to perceive (believe) that the user is performing the current task sufficiently well," i.e., that the user does not require assistance from any system agent. That goal then can be decomposed into sub-goals regarding the perception of different signs that a user needs assistance, e.g., "to perceive (believe) that the user is performing the current task in the most efficient manner." An error signal would result when inefficiencies in the user's actions are detected, leading system agents to consider intervention.

5.6.2.11 Ecological Interface Design

Ecological Interface Design (EID) is a framework for problem domain analysis and the design of human-machine interfaces in complex work environments. The approach incorporates elements from ecological psychology, particularly the emphasis on the importance of considering the interaction of humans with their environment. While most traditional interface design approaches confine their attention to human characteristics, EID also examines how humans interact with their surroundings, taking into account both physical and cognitive factors, in the context of the complex system under control. To achieve that, EID offers concrete guidelines on interface design, with the aim of producing optimal usability and safety. See [2].

EID should be considered for use in the context of applications that are safety-critical and involve high cognitive workloads.

5.6.2.12 Integrated Methodology for Help System Design

The foregoing sections presented a variety of theoretical approaches to construct a comprehensive, integrated framework for the design and implementation of an intelligent, adaptive, agent-based system for providing

help to software users. The resulting integrated methodology is composed of elements from the following design approaches:

- CommonKADS (CK) – a knowledge management and engineering methodology that guides the systematic analysis and design of intelligent systems;
- IDEF Standards – a complement to the CommonKADS methodology through its more effective support for temporal modelling and ontology construction;
- Explicit Models Design (EMD) – a methodology for building models that identify and compartmentalise the knowledge required by intelligent systems;
- Perceptual Control Theory (PCT) – a feedback control system model for goal-directed behaviour in a system; and
- Software Agent Paradigm – a software design approach that supports enhanced modularity, reusability and efficiency.

The integration of the above techniques into a comprehensive, cross-disciplinary design framework serves the goals of generating a robust, maintainable and reliable help system.

Following is a description of the recommended procedure for designing and implementing a knowledge system within that framework. Steps are designed to be pursued in the sequence presented.

To facilitate the presentation of the procedure, a legend is provided to help distinguish the models that comprise the CommonKADS (CK) knowledge and engineering methodology and those used in Explicit Models Design (EMD).

CommonKADS (CK):

Organisation Model
 Task Model (CK)
 Agent Model
 Knowledge Model
 Communication Model
 Co-ordination Model (MAS-CommonKADS)
 Design Model

Explicit Models Design (EMD):

Task Model (EMD)
 User Model
 System Model
 Dialogue Model
 World Model

5.6.2.13 Help System Design Methodology

- Construct an Organisation Model to describe the organisational structure within which the knowledge system will be used;
- Construct the Task Model (CK), including task hierarchies for all agents identified above (use IDEF3 to represent the hierarchies in applications with precise timing needs);
- Construct the Agent Model identifying all user and system agents and their relationships;
- Generate the Task Model (EMD) by extending the Task Model (CK) to produce task hierarchies for all agents using PCT-based hierarchical goal analysis;

- Develop the User Model according to the need to track user preferences and knowledge;
- Specify the content of the System Model to enable representation and use of system preferences and knowledge;
- Design the World Model to contain required information about the environment necessary for the knowledge system to operate effectively;
- Specify the Dialogue Model, Communication Model and Co-ordination Model to govern the format and content of communication among agents (ensure that the ability exists for agents to provide feedback to one another);
- Use IDEF5 to design an ontology to represent the contents of all Explicit Models;
- Develop the Knowledge Model to encapsulate the ontology and an associated knowledge base containing information from all Explicit Models;
- Within the Knowledge Model, represent the Task Model (EMD) as a hierarchy of PCT loops that use plan recognition and plan generation to form input perceptions and output behaviours; and
- Create the Design Model to produce design specifications for the target knowledge-based system.

5.6.2.13.1 Generalised Principles of Help System Design

Now that the theoretical infrastructure underlying the help system has been described, it is useful to examine some general principles for guiding the construction of an adaptive interface:

- Combine principles from CommonKADS, IDEF Standards, Explicit Models Design, Perceptual Control Theory and agent-oriented development to design and implement the system, as described above;
- Apply the five-part taxonomy within the plan recogniser to classify user interface actions in terms of user help requirements. The taxonomy of requirements includes efficiency, completeness, consistency, correctness and safety, which guide the establishment of a network of rules that enable the system to determine a user's help requirements;
- Use the results of the user needs analysis to develop plans that provide optimal help given the system's on-going knowledge of the user;
- Structure the interface to maximise the effective execution of tasks with respect to the five criteria above;
- Structure the interface to ensure that users receive continuous support in executing plans and achieving goals. A variety of support mechanisms should be implemented, including, among other things, wizards, tutorials and ongoing dialogues between the user and system. Their purpose is to help create a virtual environment where help is integrated, seamless and natural. Not only should those help mechanisms provide guidance and education on software use, but they also should structure the user's pursuit of tasks in a way that allows the system to track user goals and plans with a substantial degree of accuracy. The goal is for the system to take maximum advantage of opportunities to assist users while minimising unnecessary disruptions;
- Implement each object in the software as an intelligent agent responsible for monitoring its status relative to the five help criteria;
- Allow users to specify a "contract" with the system governing the nature of help to be provided; and
- Ensure that help dialogue encourages bidirectional feedback between the user and the system sufficient to mutual understanding.

Those items are described in greater detail in the following sections.

5.6.2.14 The Five-Part Taxonomy for Plan Recognition

In the “Perceptual Control Theory” section, a set of five criteria was introduced for use in classifying whether the user is carrying out the current task:

- Correctly;
- Completely;
- Consistently;
- Efficiently; and
- Safely.

The control loops monitoring user activity should implement rules to determine whether the above criteria are being met. When a failure is identified, the system is signalled (by one or more agents) that the user may require help. A key advantage of that approach is that the rules are not application-specific and can be implemented in any help system that includes, or can construct, a complete hierarchy of tasks and plans for the application. Additionally, most of the help information presented to users as a result of the rules can be derived directly from the task hierarchy (e.g., showing a correct sequence of actions to achieve a specific goal), greatly reducing the need to generate custom help content.

Following is a discussion of the rules that will be associated with each of the five criteria.

5.6.2.14.1 Correctness

Correct execution of plans is associated with carrying out the necessary steps in the required order. There are a few possible scenarios when the system observes a user perform an action that is not the expected next step in the currently inferred plan. For example, it is entirely possible that a user may not know what step should be performed next and has chosen an incorrect action. A user also might repeat a step in a plan, either accidentally or because of a misunderstanding about the correct procedure. Such scenarios provide opportunities for the system to offer clarification on the correct approaches.

Alternatively, a user may have abandoned the current plan, which again offers a possible help opportunity, since the abandonment may be the result of that user not knowing the correct steps required to finish what was begun.

There is also the possibility that a user has deliberately decided not to pursue the original plan, or to follow an alternate plan simultaneously. The knowledge in the User Model relating to the user’s expertise, knowledge of particular software functions and past behaviour executing tasks should be organised in a way to facilitate the system’s ability to discriminate among such possibilities. Failing that, it may be necessary for the system to ask for clarification on the user’s intentions or maintain a level of uncertainty until a clear plan sequence can be identified.

To accommodate such inference capabilities, the plan recogniser must allow for the possibility that multiple plans are being pursued concurrently.

5.6.2.14.2 Completeness

Incomplete execution of plans also can be associated with a variety of scenarios. For example, a user may omit an action while executing a plan, suggesting the system should inform the user of the missed step. A user also might stop carrying out a plan before all the steps are complete, resulting in a need for the system to identify whether abandoning the plan was intentional or inadvertent by examining the User Model and task history, and possibly asking for clarification.

Delays in completing a plan may occur when users are distracted or are pursuing another plan at the same time. In such cases, it may be desirable to present a reminder about the unfinished (suspended) task.

Some actions in certain plans will be identified as optional (either in their ordering or in their presence in a plan) and completeness rules will need to discern whether the omission of an optional step violates the completeness criterion.

It should be noted that in many cases there is overlap between the completeness and correctness criteria, where, for example, if a user skips a step in carrying out a plan, it will be both incorrect and incomplete. However, beginning a plan correctly but not finishing it would lead to a correct, but incomplete plan. In contrast, finishing a plan with an incorrectly executed step might be thought of as a “complete,” but “incorrect” plan. Such distinctions justify treating the two criteria separately.

5.6.2.14.3 Consistency

User consistency with task execution can be determined by comparing steps taken to achieve a particular goal with those taken by the user to satisfy that goal in the past. Differences can reveal a number of different things. Inconsistencies in the performance of tasks may indicate confusion on the part of a user as to the correct procedure, presenting an opportunity for the system to provide help. Inconsistencies also may reveal that a user has learned a new plan for achieving a goal, and that new knowledge should be noted in the User Model.

An important point is that an observation by the system that a user is performing a task inconsistently with his or her past behaviour may not indicate that intervention is required, unless there are signs of incorrect or inconsistent plan execution.

A user who varies his methods of carrying out plans may simply be trying to achieve variety in their execution. Knowledge of such tendencies should be stored in the User Model to facilitate future classification of user activity according to the five criteria.

Establishing consistency requires knowledge of past activity and the system will not have that historical data for users who are new to the help system. Because inexperienced users likely will require immediate help, default settings for typical users will serve as a starting point for building a user profile. For intermediate and advanced users, however, the system may conduct a period of observation to become familiar with that user's preferences, needs and methods.

Maintenance of activity profiles should be an ongoing process for both novice and expert users. The system should analyse history information contained in the Task Model for a user to determine preferred plans for accomplishing goals and knowledge of software features. By performing such analyses, historical task data can be archived more concisely and accessed more quickly.

5.6.2.14.4 Efficiency

A simple rule for identifying inefficiency in user actions would compare the current plan with alternate plans for achieving the same goal. The presence of another plan with fewer steps suggests that the user should be informed of the simpler alternative.

There may be situations where alternate plans require the same number of steps, but where one would be considered more efficient. For example, selecting a menu item using a keyboard shortcut is often faster than using the mouse to pull down the menu. Also, some keyboard shortcuts are easier to perform than others, such as pressing the Delete key instead of Ctrl-X to delete an object. A system of rules should take such factors into account and assess the relative ease with which competing plans could be executed.

Another issue is that a particular action may be more or less efficient depending on the other actions that are part of the same plan. For example, if a user has been typing data into a dialogue box, it typically will be most efficient to press the Return key to dismiss the window. However, in circumstances where the user's hand is already on the mouse, it would be easier to click the OK button. Rules in the knowledge system should evaluate the efficiency of steps in the context of the broader plan.

A final rule-based method to increase user efficiency involves identifying plans that the user is pursuing that could be completed by the system without further input from the user. In such situations, the system either could automatically complete the task for the user, or could offer to do so with the user's approval, depending on the selected automation level in the user's contract with the system. In order to offer such capabilities, the help system should be able to distinguish between actions in the goal and plan hierarchy that require human input and those that do not. An example of a task requiring no human input is the ability of most web browser software to enter information into online forms automatically.

5.6.2.14.5 Safety

Safe execution of tasks will not be a critical issue in all applications, but in some domains (e.g., aviation, industrial process control), the safety of humans and equipment can be a deciding factor.

In practically all software applications there is a safety issue surrounding the avoidance of data loss. A simple example of a safety mechanism is the standard prompt to save changes when a file is closed, but more involved methods can be imagined. For example, new users could be presented with additional warnings when deleting complex objects, reverting to default settings or carrying out other tasks where a substantial amount of information could be erased inadvertently. The availability of a "multiple undo" capability helps reduce the risk of irreversible violations of safety criteria.

5.6.2.15 The Five-Part Taxonomy for Plan Generation

The on-going user-needs analysis, described in the preceding section, is responsible for determining whether or not a user requires help with respect to each of the five help criteria. Deciding when and how best to provide that help falls to plan generation techniques.

Generated plans will depend on the nature of a user's need for help. Following is a description of help needs as they fall within the five-part taxonomy.

5.6.2.15.1 Correctness

If a plan is being pursued incorrectly, it is likely that the user should be informed about it promptly. For example, if an incorrect step is performed in a plan, the user will need to know that his goal may not have been satisfied since the plan was executed incorrectly. Thus, the correct procedure for accomplishing that goal should be conveyed to the user promptly and directly, perhaps through the use of an immediate help window.

On the other hand, when there is system ambiguity as to whether a user is carrying out a plan incorrectly, or has simply abandoned it altogether, it will be useful to present that user with a question about her intentions. The help system should allow clarification questions to be presented to users in a non-disruptive fashion, such as through the use of a floating window. Although responding to such questions will be at a user's discretion, doing so will improve the help system's model of that user, and therefore its ability to provide useful help to her.

A user may wish to monitor plans that the system believes she is pursuing and that could inform her that an action is not a correct part of the current plan. That monitoring could occur in a window showing the currently inferred plan in the context of higher-level tasks, as well as what the next action should be. It also could alert the user that the system believes she is pursuing some goal other than her true goal. A mechanism could be provided for the user to correct the system's misunderstanding by specifying the actual plan being pursued, which will provide a learning opportunity for the system. While most users will not find it practical to monitor such a display continuously, it will be very useful in situations where users are unsure of correct procedures. Providing a monitoring mechanism for a user could provide opportunities to understand how such information might be organised and presented more effectively in future. It could serve as an experimental design element with some option for user feedback.

5.6.2.15.2 Completeness

An incomplete plan can be the result of a user omitting a required action during its execution and, as such, it is important to inform the user of that omission. In those cases, a help window should be displayed immediately so that the user may correct the error and achieve the intended goal.

Incompleteness may also result from abandoning a plan and pursuing another in its place. In such cases, it may be important to establish through a clarification dialogue whether the abandonment was the result of a shift in intentions or if it arose because the user lacked required knowledge. The latter case would signal a need to present the missing knowledge. A user might also abandon a plan with which he is unfamiliar in favour of one that he is confident will work. In that case, and under the right circumstances, the system should offer assistance on the initial plan about which he was unsure. Situations where users are pursuing multiple simultaneous plans or have been distracted would not warrant intervention from the system, but provide an opportunity for clarification. Questions seeking clarification should be presented unobtrusively, since it will not always be possible for a user to suspend the current task to respond to the help system. Clarification questions may be presented in, for example, a help system status line, to enable users to monitor system activity. In situations where the user fails to notice the question within a reasonable period of time, the system should alert him to its presence. Care must be taken to make such alerts noticeable but not intrusive and, where possible, context should be considered before displaying the alert. In applications where space is insufficient to present questions in full, a discreet notification may be used, such as the display of an icon. The "Plans for Providing Help" section, below, offers further discussion of methods for presenting clarification questions.

5.6.2.15.3 Consistency

Some inconsistent behaviour on the part of a user may indicate confusion as to how to achieve current goals. Unlike correctness and completeness, the consistency criterion often will not be associated with an overt sign that the user requires assistance and so, typically, will not call for the same immediate presentation of help information. In those cases, it will be more appropriate to use a less overt form of help, such as waiting for a pause in a user's activities before presenting information, or displaying a subtle prompt to tell the user help is available.

5.6.2.15.4 Efficiency

As with consistency, the efficiency criterion usually is not associated with problems in completing the current task and, therefore, an inconspicuous or delayed form of help is also appropriate. Delayed help will be presented upon completion of the current plan, at idle time, at the end of the session or under other circumstances that will not disrupt user performance.

5.6.2.15.5 Safety

The safe execution of tasks is associated with a high priority for conveying help to the user. Unsafe acts may or may not involve risk to human safety, but there may be risks of data loss. Help information relating to safety will necessitate immediate notification of the user in a conspicuous manner, such as with an auditory signal accompanying a dialogue box requiring user acknowledgement.

When accidents occur in safety-critical domains, such as aviation, they are typically followed by investigations to identify their attendant causes. An accident occurring in the context of a user interacting with an intelligent system provides an opportunity for investigation results to assist software developers in redesigning systems to prevent future accidents. The software application, Systematic Error and Risk Analysis (SERA) Tool, was developed to help accident investigators identify failures and their pre-conditions using principles of Perceptual Control Theory. Results of investigations using SERA would be useful to designers seeking to build safer software systems.

5.6.2.16 Plans for Providing Help

Help can be offered to users in a variety of forms:

- A “wizard” interface to guide the user through a complex process, such as creating a workspace and configuring its contents (see the next section on “Wizards”).
- Tutorials tailored to a user according to what the system believes the user knows. It may be presented according to a prearranged schedule resulting from an agreement (PACT “contract” – see “The PACT Approach and Automation Levels” section, below) between the user and system (e.g., a weekly mini-tutorial on a feature with which the user is not familiar).
- Interactive tutorials, whereby the system steps through a description of a procedure while the user carries it out.
- Tutorials providing guidance on how to solve an application-specific problem that a user is confronting. That would occur, say, in response to a user asking, “How do I finish this [the task the user has begun]?”.
- Presentation of a question asking if the user would like assistance or a question asking for clarification of a user's intentions:

Such questions could be displayed in a help system panel within the main application window, and could be accompanied by one or more indicators, such as light bulb icons, to show the availability of messages from the help system. A small panel could show the current question or partial text of that question so a user could decide whether to respond. If the user did not respond within a specified time, the light bulb icon and question would flash two or three times to attract the user's attention. The question would disappear if it continued to be ignored, perhaps after a second round in which the light bulb flashed. Users still should have the option of reviewing that material at their convenience, at the end of a session or in other circumstances deemed appropriate; and

If the system observed a prolonged period without user activity, it might reasonably conclude that the user had suspended activity and was away from the computer. In such a case, the presentation and other system-related activities with respect to help signals to the user would be delayed until work with the software resumed.

- During any review of system proffered help, users would be able to examine the context in which it was determined that help was appropriate, specifically the context of attendant user actions and system-inferred goals and plans from those actions. The display of questions and optional review will be controlled as part of the user's PACT agreement with the system (see "The PACT Approach and Automation Levels" section, below).
- Presentation of web-based help.
- Display of a light bulb or other alert indicating the availability of help information when selected.
- Brief pop-up descriptions of interface elements when the mouse is "over top".
- An offer to complete a task that the user has started.
- Periodic presentation of tips with which the system believes the user is unfamiliar.

5.6.2.16.1 Wizards

To further the goal of creating an interface in which users receive continuous support in executing plans and achieving goals, a variety of wizards should be available to users. The wizard interface approach offers a number of advantages:

- It simplifies tasks for users because the system takes care of detailed plans and contextual supports along the way, making it useful for both novice and expert users;
- Incidental learning occurs when users are guided through procedures for achieving high-level goals;
- By stepping a user through a well-defined procedure, the help system can infer the user's intentions with much greater confidence (especially true for novice users) than if he were proceeding on his own initiative. That substantially increases the relevance and usefulness of help offered by the system about the task; and
- Given the built-in constraints on task execution, there will be fewer opportunities for plans to violate any of the help system criteria.

To help design and implement a wizard, scenarios will be developed to describe how typical knowledge elicitation sessions proceed. That information will be useful in establishing specifications for audio wizards, described next.

5.6.2.16.1.1 Audio Wizards

Consideration should be given to the creation of a wizard interface that uses an audio dialogue between the user and system. Reliable speech tools are now widely available and the incorporation of those techniques into a help system is a logical way to make dialogue more natural between the system and user.

In an audio wizard, questions are posed using software speech generation and spoken answers from users are interpreted using speech recognition. Questions should be phrased to limit the range of possible responses to ensure high recognition accuracy.

5.6.2.17 Control Loop Design

5.6.2.17.1 Centralised System Model Control Loops

Responsibilities for determining user help needs are divided among the System Model and agents associated with individual interface objects. Control loops in the System Model should monitor user actions and apply the general rules identified in the earlier section, “The Five-Part Taxonomy for Plan Recognition.” That includes a hierarchy of rules based on those introduced in the “Perceptual Control Theory” section. A high-level description of control loop goals is as follows:

To perceive (believe) that...

- ...the user is performing the current task sufficiently well and does not require help;
- ...the user is performing the current task efficiently;
- ...there are no plans with fewer steps available to achieve the current goal;
- ...there are no more efficient plans of the same length to achieve that goal (e.g., shorter time requirements or greater convenience for the user);
- ...the user is performing the task correctly;
- ...the user has not performed a step that is not in the current plan;
- ...the user has not performed steps in the current plan that are out of order;
- ...the user has not repeated a step in the current plan unnecessarily;
- ...the user is performing the task completely;
- ...the user has not omitted one or more steps in the current plan;
- ...the user has not suspended the pursuit of a plan;
- ...the user is performing the task consistently;
- ...the user has not behaved in a manner inconsistent with past task performance;
- ...the user is performing the task safely; and
- ...the user is performing the task consistent with the integrity of key human, machine and data elements of the total system.

5.6.2.18 Objects as Intelligent Agents

All interface objects in the target software should be implemented as a network of intelligent agents, which has the effect of increasing modularity, organisation and reusability among help system components.

(See the “Software Agent Paradigm” section)

Agent-based objects are to include all standard interface elements, such as windows, buttons and menu items, as well as application-specific objects. Each agent is responsible for monitoring its own status relative to the five help criteria, described earlier. Those include checking the following properties:

- Correctness – e.g., that the value of a variable or the contents of a text box is within an acceptable range;
- Completeness – e.g., that all data have been entered for a particular object;
- Consistency – e.g., that data are consistent with the execution of current tasks;
- Efficiency – e.g., that a frequently used menu item is associated with an easily accessed keyboard shortcut; and
- Safety – e.g., that some agents will have tendencies for self-preservation, particularly where loss of data is a risk.

Agent processes monitoring those criteria should be continuous and System and User Models should be able to query agents as needed.

Agents should monitor the usage of their associated objects by the current user and store important information, such as when they were first accessed, the most recent access and the number of times they have been accessed. That information will be available for compiling User Model knowledge about software features and user familiarity with them.

As noted earlier in the “Centralised System Model Control Loops” section, the System Model should monitor user needs in the context of the general rules of the five-part taxonomy. Specific rules should be associated with interface objects and their agents.

5.6.2.19 The PACT Approach and Automation Levels

Since it is unrealistic to expect that all users will require the same level of automation from an intelligent system at all times, a need exists for users to be able to specify their requirements of the system. In the help system, circumstances of a particular task and operator preferences will dictate what automation level is most appropriate, and those could change over the course of a session.

One method of handling automation levels in the air domain is the Pilot Authorisation and Control of Tasks (PACT) system. That approach is based on the notion of contractual autonomy, in which a user and system establish an agreement, or contract, on the system’s responsibilities. Contracts are made using a system of six levels, numbered from 0 (no automation) to 5 (fully automatic). Table 5-4 shows the levels of autonomy in the PACT approach.

Table 5-4: PACT Levels of Autonomy

Levels	Operational Relationship	Computer Autonomy	Pilot Authority
5	Automatic	Full	Interrupt
4	Direct Support	Advised action unless revoked	Revoking action
3	In Support	Advice, and if authorised, action	Acceptance of advice and authorising action
2	Advisory	Advice	Acceptance of advice
1	At Call	Advice only if requested	Full pilot, assisted by computer only when requested
0	Under Command	None	Full

Contracts in a help system should offer users the ability to set the autonomy level and change it at any time during a session, as well as provide the flexibility to customise the provision of specific forms of assistance. That customisation should allow users to request help at specified intervals or to ask that help be provided in a specified form.

In order to aid in deciding the most appropriate level of assistance to offer a user given the selected autonomy level, the system should maintain a set of numerical scores in the User Model to indicate the preferences and needs of the current user. Those act as thresholds in determining when the system should intervene, based on:

- System beliefs that the user possesses relevant knowledge;
- Feedback from the user in response to each help offer from the system, either by using a “Don’t show again” button or by ranking the usefulness of the information on a scale of 1 to 10, as in, “How would you rate the value of this help?” The system also should have the ability, at least in some circumstances, to judge the suitability of displaying a message again, even without a user selecting the “Don’t show again” option. In most cases, after information has been displayed and acknowledged by the user, the system will infer that knowledge will not need to be presented again, unless subsequent user actions demonstrate that it was not understood or has been forgotten;
- General feedback from the user on preferred types of help, based on online questionnaire responses from the system on favoured techniques. Such a questionnaire could elicit general information on the efficacy of help provided to a user, perhaps at the end of a session. The PACT contract will allow users to enable or disable the feature according to their desire for such a feature;
- Historical system knowledge of techniques that have been most effective at conveying information to that user in the past, revealed by acknowledged help messages and demonstrated task knowledge; and
- State of completion of the current task, so as to avoid unnecessary disruption.

5.6.2.20 References

- [1] Schreiber, G., Crubézy, M. and Musen, M. (2000). A Case Study in Using Protégé-2000 as a Tool for CommonKADS. EKAU 2000: 33-48.

- [2] Vicente, K.J. and Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man, and Cybernetics, 22, 4, 589-606.

5.6.3 Autonomous Decision Making for an Underwater Unmanned Vehicle

5.6.3.1 Underwater Unmanned Vehicles

Unmanned vehicles have been around for some years in all environments – on the ground (UGV), in the air (UAV), surface water (USV) and underwater (UUV). More strictly, these have been primarily in the category of remotely operated vehicles (ROV), in that there are command and communications links (direct or via satellite) to a remote human operator, who maintains full system control at all times.

In the UAV field in particular, the effort is directed at improved data fusion and representation, in order to allow the human operator to control several UAVs at once, furnishing the vehicles with autonomy over lower level functionality, but nowhere near full autonomy. Underwater ROVs tend to be tethered to a mother ship via an umbilical cord, supplying power and command and communications links [1].

The free swimming UUVs tend to be very small, of limited endurance, with a single specific task, such as inspection of underwater objects [2]. In all these cases the man is being kept firmly in the loop.

However, the envisaged operational environment for military UUVs precludes such an umbilical link and, indeed, for certain mission phases, any sort of communications with the vehicle at all. This will require the UUV to possess the capabilities to perform all the tasks to be performed, from navigation, power monitoring/management, threat identification and avoidance and payload delivery, through to the far less concrete area of high level decision making in the face of high levels of uncertainty.

The power source will also have to be wholly internal to the vehicle. This is currently based on batteries, although it is likely that fuel cells will replace these as the technology improves. Even the latter will only yield a useful energy output of about 400 Wh per kg, with the potential to (possibly) double this figure within the next 5 years. With current UUVs, such as the USS Manta, requiring up to 50 kW for propulsion alone, plus several kW more for sensor operation (e.g., sonar), the size of the problem of supplying sufficient power to allow the performance of any kind of mission becomes apparent.

The addressing of this power management problem, which is usually denoted by HOTEL, What does HOTEL mean? It boils down to answering the question ‘can I do the mission and return to my recovery point on my power reserves?’. This baselining of the projected energy consumption for the whole mission, continually updated during the mission, underpins every other assessment and decision made during the mission.

5.6.3.2 Envisaged Theatre of Operations for Military UUVs

The US Navy envisage the littoral zone to be the most important for UUV operations [3], from mine counter measures prior to a naval assault, through coastal and channel mapping via sonar, to deploying sonars near enemy naval installations to track asset movement and even kill them with torpedoes. This poses certain problems, from vehicle design through to sensor operation. The traditional teardrop shape is the most efficient, from a drag minimisation point of view. However, this is not appropriate for very shallow waters, giving rise to a significant risk of running aground. Here, a thinner, flatter, more Ray-like profile is more appropriate (e.g., Manta), with a higher power consumption as a result. Conventional sonars will have their performance degraded significantly from bottom clutter in the shallows.

There are, however, research efforts directed at biomimetic sensors, emulating the capabilities of the sonar systems of dolphins, which do not suffer significantly from such problems. This will be crucial, as, in all these projected scenarios, the UUV will be totally reliant on a main forward sonar and left and right short range sidescan sonars to prevent it from running aground (or into obstacles), as it follows the coastline or navigates through narrow channels.

5.6.3.3 Approach to Automation and Decision Making

Whenever we automate any process, there are certain risks associated with that automation. Obviously, in some cases these risks are lower than in the equivalent manual process, in others they are higher. The 3 risk factors of primary concern here are those relating to communication (right information at the right time), workload (system overload) and unpredictability (moving outside the zone covered by prior knowledge and experience).

Figure 5.31 provides a schematic representation of the change in adaptiveness vs. levels of human control, automatic control and cognitive cooperation, for these 3 important risk factors of communication, workload and unpredictability. This displays, in particular, the greater susceptibility of human operators to increased workload vs. an automated system and the reverse in the case of increased uncertainty. Any ways in which we can improve the way an automated system can handle uncertainty will be of particular benefit in the context of an autonomous system.

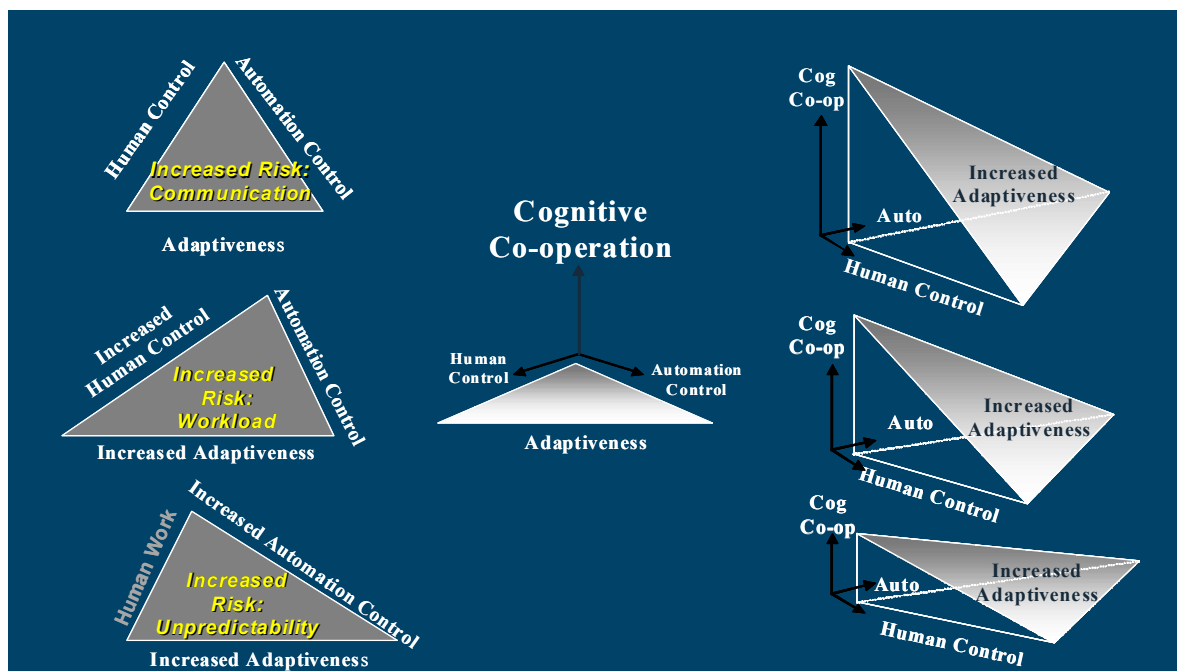


Figure 5-31: Cognitive Co-operation and Human vs. Automation Control.

This is explored further in Figure 5.32, which addresses leveraging autonomy through cognitive automation. This represents the opportunity for pushing the boundary back between what can be achieved in an automated system (traditionally skill and rule based behaviour) and that, knowledge and experience based area that requires human control. This requires the ability to reason effectively in the presence of significant levels of

uncertainty. This can be based on a combination of model based reasoning and a suitable methodology for resolving situations in which no clear decision is forthcoming, due to conflicting objectives, etc. (e.g., neuro-fuzzy or genetic algorithms, e.g., [4]).

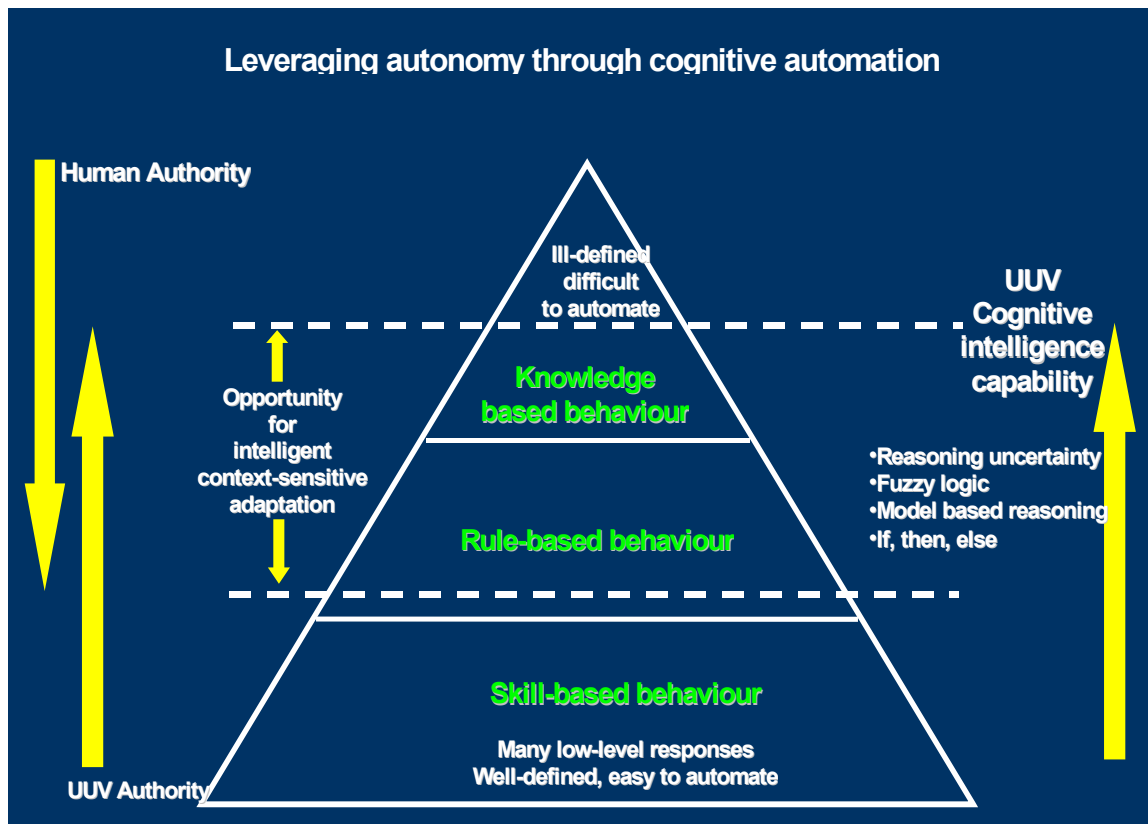


Figure 5-32: Leveraging Autonomy through Cognitive Automation.

The underlying requirement is for a system that can provide for dynamic, context sensitive adaptiveness, so as to engage each task at the appropriate level of autonomy.

It is useful here to simplify the different (cognitive) levels of tasks into 3 groups, namely system health monitoring, mission control and strategic control. Figure 5.33 shows the progression of the dividing line between automated control and human control, from manned underwater vehicles, through the traditionally understood uninhabited vehicle, to an unattended cognitive underwater vehicle, which is an intermediate stage on the way towards our goal of a wholly autonomous (cognitive) underwater vehicle. The aim is to steadily push the dotted line to the top of the triangle, through improved reasoning and uncertainty handling processes. The causal reasoning process can be represented in terms of a decision ladder, consisting of a clear series of knowledge states, linked by processes which determine the flow between these states (a state flow representation).

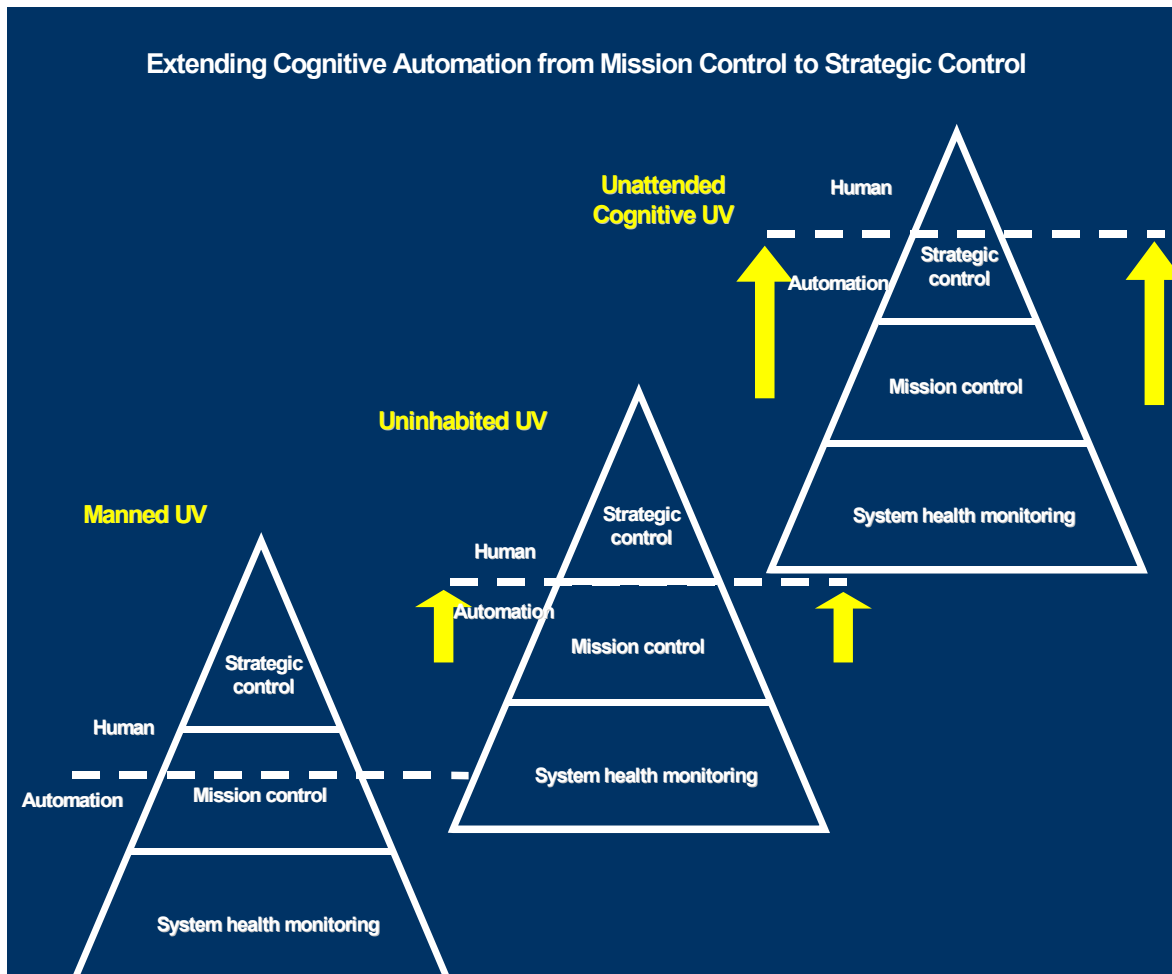


Figure 5-33: Transition from Manned, through Current Unmanned, to Semi-Autonomous Underwater Vehicle.

A general process of adaptiveness is shown in Figure 5.34. Such a state flow representation of a system is, in effect, a finite state machine representation of it and, therefore, by definition tractable. It can be characterised by the traditional measures from information theory (Kolmogorov Complexity [9], Fisher's Information Measure [10], Shannon's Negative Entropy [11], etc.).

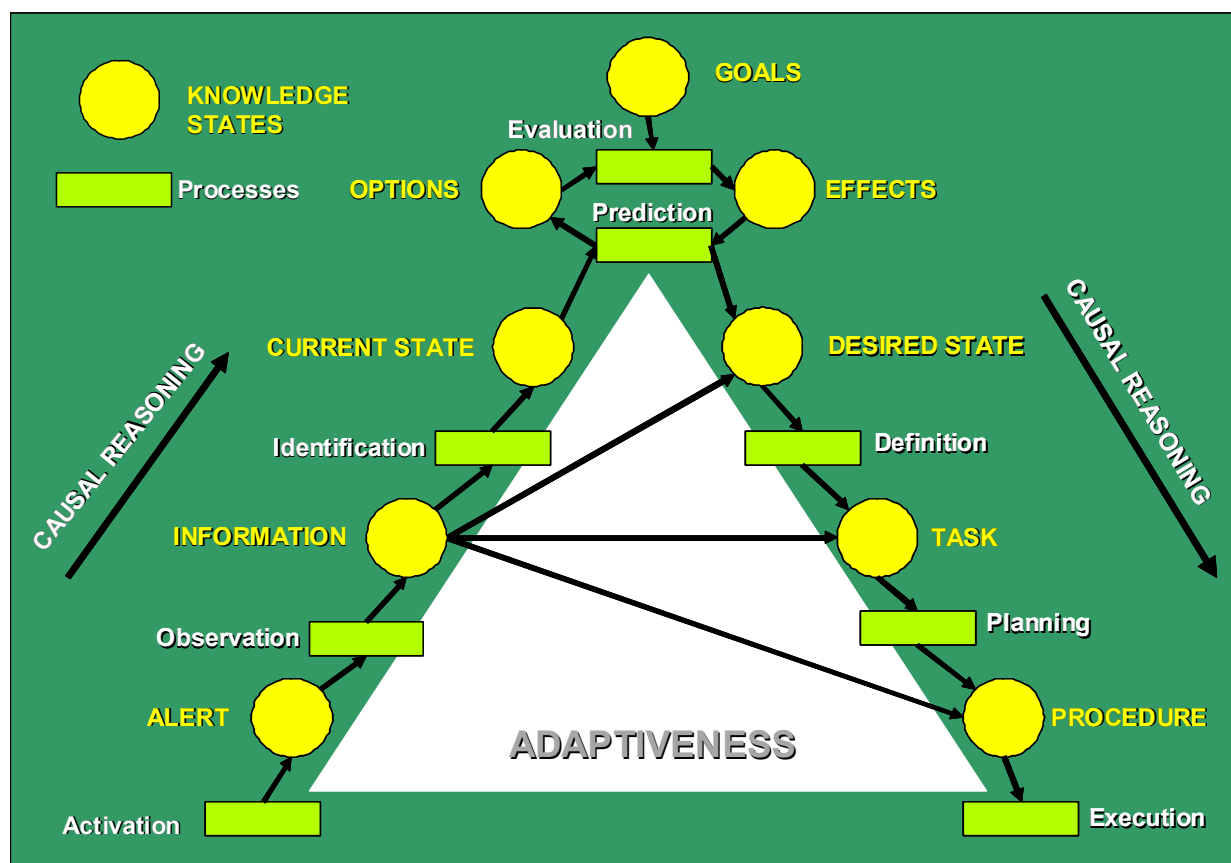


Figure 5-34: Decision Ladder Framework for Task Decomposition.

In particular, the aim is to minimise the Kolmogorov Complexity of the system representation. In effect, minimising this equates to an Occam's Razor approach to decision making and problem resolution. This is defined as the shortest algorithm that fully represents the total information content of a given system. In practice, we will not have the full information content of the system (i.e., mission) and will be operating on a best approximation to that. This arises directly from the, at times considerable, uncertainty that may be present during the course of a mission and any resultant conflicts within the decision process.

PACT (Policy for Authorising and Control of Tasks) provides a convenient system for identifying levels of autonomy in a system (Commanded; Assisted – At Call, Advisory, In Support, Direct Support; Automated). The system is one that has been applied at DERA previously for addressing decision aiding and support in the Cognitive Cockpit Programme [5,8]. The aim in improving the ability of an autonomous vehicle to handle higher level functions and tasks and environments with significant levels of uncertainty associated with them, can be expressed directly in terms of increasing the PACT level of tasks from that currently attainable. As an example, Figure 5.35 provides a possible PACT Contract Level diagram for a set of 'typical' tasks, in 4 groups, over a 6 phase mission for an intermediate type of autonomous underwater vehicle, as in Figure 5.35. Those tasks with a PACT level below 3 do not involve suggested courses of action from the vehicle for the human controller; they require direct initialisation by that controller. The PACT Scheme provides a useful tool in aiding this process, allowing a direct visualisation of the dynamically changing autonomy structures within the system.

Possible UUV PACT Contract Levels									
				Launch	Transit	Search	Recovery tp Position	Transit	Recovery tp Position
AUTOMATIC	5	Control Vehicle	Capture target			5			
			Avoid target			5			
			Terrain avoidance	5	5	5	5	5	5
DIRECT SUPPORT <i>i</i> ACTION	4	Navigate	Identify waypoints		4		4	4	
IN SUPPORT <i>i</i> (ACTION)	3		Monitor position	5	5	5	5	5	5
ADVISORY <i>i</i>	2		Update route plan		3		3	3	3
AT CALL <i>(i)</i>	1	Manage Systems	Manage DAS	4	4	5	4	4	4
COMMANDED	0		Manage weapons	0	0	5	0	0	0
			Manage fuel	5	5	5	5	5	5
		Manage Mission	Manage unexpected	0	0	5	0	0	0
Progress time mgt	2		2	5	2	2	2		
Assess situation	0		2	5	2	2	0		

Figure 5-35: Possible PACT Contract Levels for a UUV Mission.

5.6.3.4 Multi-Agent System Representation

Recent work addressing dynamically adaptive autonomy in multi-agent systems [12,13], puts forward a framework that permits agents to dynamically form, modify or dissolve goal-oriented problem solving groups. In particular, it enables these agents to do so in the presence of high levels of change and, ultimately, uncertainty. It provides them with the key ingredients that permit the transition from adaptability to adaptation – motivation and the ability to change the problem-solving framework of the system itself.

In addition, [12] introduces the concept of the sensible agent, which participate in a two phase process prior to engaging in tasks, namely:

- 1) A decision-making phase, during which sub-tasks designed to carry out the goal are identified and agreed upon; and
- 2) A task allocation phase, during which the various agents are assigned actions and tasks, in accordance with the decisions made.

The point is made that agents using any autonomy model must comprehend the concepts of ‘self’ and ‘others’. An example would be the sensor system processor cooperating with the navigation system processor to prevent the vehicle running aground or colliding with an obstacle. To achieve this, each agent must possess its own environmental model, such that it can understand the implications of the information it is receiving for any of the other agents and act accordingly.

A constrained version of this model can be applied to the case of multi-processor platforms, such as UUVs (e.g., Manta), where certain actions must, by definition, be performed by a particular agent (i.e., processor) and where there is a requirement for a single focus for enacting the overall mission plan.

This is most conveniently achieved via the fact that UUVs normally possess a central, or main, processor, which can be permitted to act as arbiter in task assignment and decision-making in general, fulfilling, as such, the role of a local master.

It can also, where operational conditions permit, facilitate the dissemination of relevant information between agents, to augment their common knowledge base (i.e., corporate knowledge). Moving beyond the level of the individual platform, within the context of Network Enabled Capability (NEC), this approach may easily be scaled so as to encompass cooperation among any number of unmanned platforms, in order to achieve a common mission objective.

5.6.3.5 Autonomous Underwater Decision Making

Dstl work has provided a simulation of key aspects of the core UUV functionality in an “unattended cognitive underwater vehicle” (UCUV) autonomy project. This work is intended to provide partial proof of concept demonstration of specific autonomous decision making activities by unmanned vehicles using a navigational exercise. This work is in its early stages of development and there is a long way to go to realise the ultimate aim of a wholly autonomous cognitive underwater vehicle. Figure 5.36 provides an overview of the various inputs and contributing components for this modelling process.

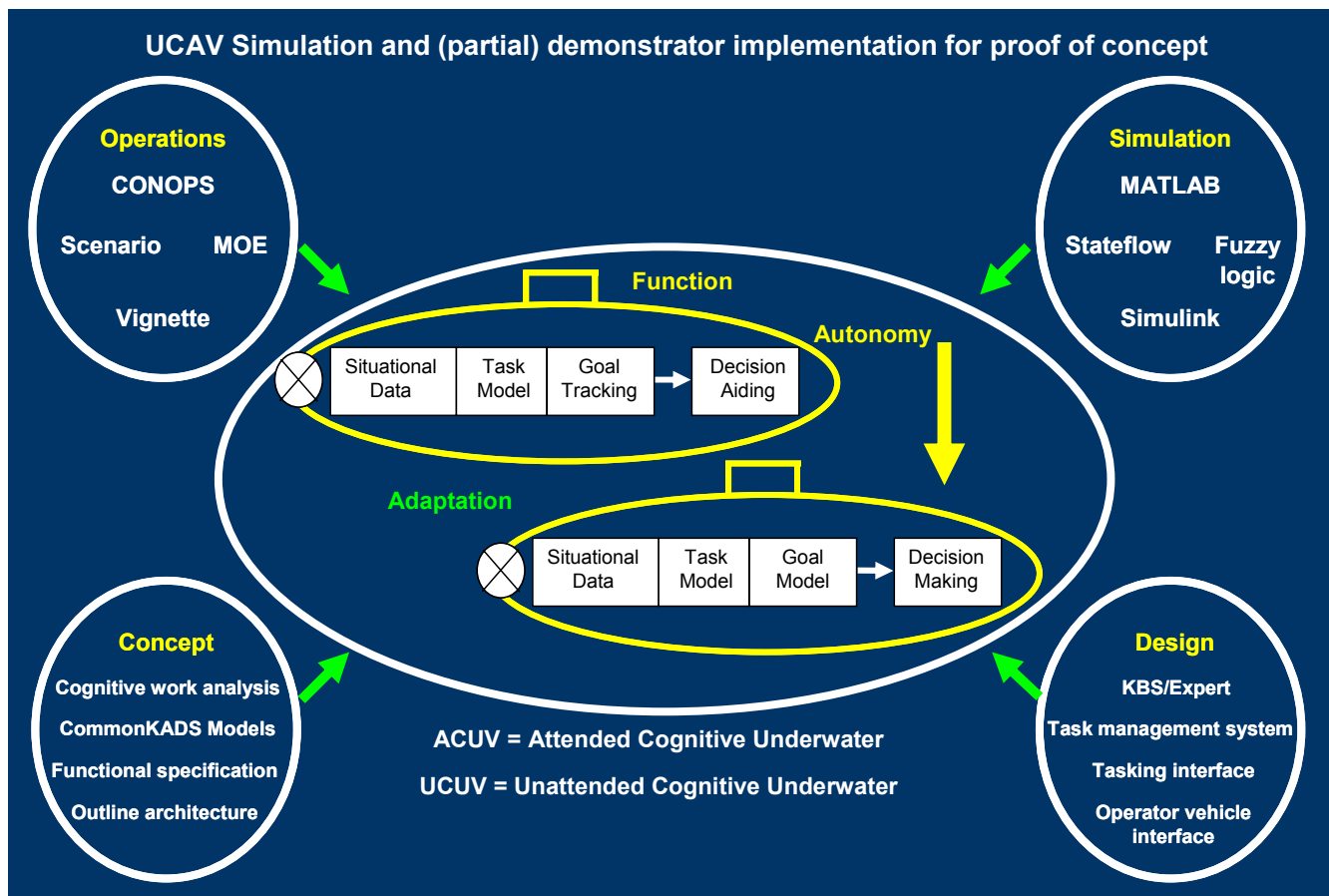


Figure 5-36: Tools and Techniques Drawn upon in the DSTL UCUV Work.

The work on UCUV artificial intelligence engine development has two facets:

- 1) The development of a knowledge based system for “inside-the-envelope” decision making [14]; and
- 2) The development of a Bayesian based learning techniques for “outside-the-envelope” decision making [15].

In order to capture a capability to handle ‘within the envelope’ higher level decision making (i.e., based on direct knowledge), a core knowledge base has been constructed to encompass a subset of the relevant drivers and principles involved [14]. Initial knowledge acquisition (KA) focussed on UUV navigating to a given target (identified by Rapidly Deployable Sonar) whilst avoiding charted objects en route. Using CommonKADS knowledge modelling methodology [16,17], further KA enabled knowledge models to be constructed, from which an intelligent routing application was specified, designed and implemented.

In a fully autonomous system, without recourse to guidance from a human operator, all of the problems that may be encountered must be resolved on-board and an appropriate decision made in all cases. So, where the situation encountered lies ‘outside the envelope’ for this knowledge base, or where no clear cut decision can be made for some other reason, an alternative decision engine will be needed to apply to the process, to force the issue.

Based upon a survey of the relevant literature, a Bayesian learning based decision engine was decided upon for addressing these “out of envelope” situations [15]. This was adopted because of the inherent advantages of the approach over alternatives such as neural networks, for handling ‘out of the envelope’ situations, where a traditional expert system type approach is inapplicable. Of particular utility here is its’ robustness in the presence of high levels of uncertainty. An incremental variation on this approach, the Bayesian Agent, was also identified, which offers a capacity for both on-line and off-line learning [18].

This survey also identified several priors of potential utility here. In order to evaluate these various options, a simulation exercise was conducted on narrow channel navigation scenarios for a simulated estuary environment.

The work employed the MATLAB modelling environment since this permits a rigorous top-down design methodology to be applied to the construction of the model, for configuration/life-cycle management purposes. This system also permits the pull through into C code of the model components directly from the model itself. Stateflow is a part of the MATLAB suite, which allows the construction of block based models of finite state machines, through the Simulink dynamic simulation system.

A stylised simulated estuarine environment (1000 m x 500 m x 25 m deep), populated with a rough terrain bed and traversed by a simulated narrow navigation channel, cut through the bed to the bottom, was chosen for reconstruction in simulation.

As a result of an extensive literature search, two alternative Bayesian based approaches were selected for comparison (MML and BCPN). What does this mean? Naïve Bayesian learning was employed on the network as a control in the exercise. In addition, an initial investigation was made into the suitability of using an ARTMAP, What does this mean? neural network approach to selection of appropriate prior distributional forms for the system [19]. The problem that was posed to each of the Bayesian systems, was: Given the current direction of travel, provide the system with any changes of direction that are required, so as to maintain a course that is as close to the centre of the channel as possible, at all times.

To, this end a 20 m by 20 m ‘window’ (i.e., the width of the channel) was used, to simulate a required clearway for safe passage of the craft through the channel. As our system has a 1 m grid size, with each of the mesh points representing the centre of a 1 m by 1 m by 1 m block, this translated itself into a 19 mesh point by 19 mesh point grid, which was required to be maintained clear of solids. For this exercise, no obstacles were placed upon the bed of the channel. However, the trained classifier can be used with equal effectiveness upon the task of avoiding obstacles in the vertical direction.

All three of the Bayesian learning network underpinned approaches investigated can provide, within certain limitations, a means of navigation through narrow, sinuous channels, through the provision of suitable course corrections. The introduction of signal degradation does impact on the performance of all three approaches, but not catastrophically so (graceful degradation). By limiting the required course corrections required to the range of ± 3 (1 m) grid points per correction, the errors in the corrections supplied all lie with the range of ± 1 grid point (rounded) after 10 training scenarios, even for relatively noisy data ([0.0,0.4] for 0.0, [0.6,1.0] for 1.0). Due to the much higher computational requirements for the MML approach, coupled with it not providing superior performance to either of the other 2 approaches, it is not considered to be suitable for use for such a task.

The use of an ARTMAP based classifier to select the most appropriate prior form for the nodes in a Bayesian network shows some initial promise. Its use in such a role requires further investigation though.

The BCPNN based approach [20,21] was recommended for pull through into native C code for further testing against a scenario based on real GIS data. This was trained on the training data set, with applied noise levels giving up to 80% reduction in signal separation between land and water, which was that applied to the signals for this test. It was then applied to a compressed section of the Columbia River, providing a tortuous path, with frequent narrowing and shallowing to below the 20 m diameter of the training data channels. This test was successful, with the course followed being within 1 m of the mid line (i.e., 1 grid point).

Overall, the test of the BCPNN approach on real data, based on a section of the Columbia River, with significant 'out of the envelope' behaviour, in terms of narrowing and shallowing, was a success. This shows the robustness of the Bayesian approach itself and also significant promise for the application of the 'abstract and simplify' approach adopted here, in the context of noisy (to 80%), information-poor environments.

The task was extremely challenging since this was a new domain for the application of Bayesian based decision making methods. The methodology is widely applicable, rather than domain dependent.

The overall aim of the work was to provide an initial investigation to provide proof of concept of decision making in support of autonomous UUV operation. This has been accomplished successfully, albeit in a limited way. The project needs to explore and illustrate the use of the developed methodology on a wider subset of the potential problem set.

5.6.3.6 Conclusions

The demonstration of the robust applicability of the principles and approach adopted, to the solution of realistic and relevant problems, certainly indicates its potential worth. This work is innovative in its very nature, particularly within the field of autonomous decision making for unmanned vehicles. It forms an exploration of the possible. However, it is an exploration based firmly on sound mathematical and statistical principles. There is a need to investigate the application of the approach and implemented algorithms to other important noisy and/or information poor decision situations, within the context of projected UUV operational scenarios. Ultimately there is a need to address higher-level decision making tasks in order to provide an integration and a synthesis of the processes, especially within the context of the future network enabled environment.

5.6.3.7 References

- [1] Wayamba. (2000). An Experimental Uninhabited Underwater Vehicle. Anderson, B. Paper presented at: Advanced Underwater Technologies for the 21st Century, Tokyo, 23-26 May.
- [2] Utyakov, L.L. (2000). Small Sized Underwater ROV. Paper presented at: Advanced Underwater Technologies for the 21st Century, Tokyo, 23-26 May.
- [3] US Naval Research Advisory Committee Report (November 2000). Unmanned Vehicles (UV) In: Mine Countermeasures (U).
- [4] Wang, P. and McKenzie, E. (1999). A Multi-agent based Evolutionary Artificial Neural Network for General Navigation in Unknown Environments. Edinburgh.
- [5] Taylor, R.M., Abdi, S., Dru-Drury, R. and Bonner, M.C. (2001). Cognitive cockpit systems: Information requirements analysis for pilot control of cockpit automation. In: D. Harris (Ed), Engineering Psychology

and Cognitive Ergonomics, Aerospace and Transport Systems. Vol. 5, Chapter 10, pp. 81-88. Aldershot: Ashgate.

- [6] Taylor, R.M. (2001). Cognitive Cockpit Systems Engineering: Pilot Authorisation and Control of Tasks. In: R. Onken (Ed), CSAPC'01. Proceedings of the 8th Conferences on Cognitive Sciences Approaches to process Control, Neubiberg, Germany, September 2001. University of the German Armed Forces, Neubiberg, Germany.
- [7] Bonner, M., Taylor, R.M. and Miller, C. (2000). Tasking interface manager: Affording pilot control of adaptive automation and aiding. In: P.T. McCabe, M.A. Hanson, and S.A. Robertson (Eds.), Contemporary Ergonomics 2000, pp. 70-74. London: Taylor and Francis.
- [8] Taylor, R.M., Brown, L. and Dickson, B. (2002). From Safety Net to Augmented Cognition: Using Flexible Autonomy Levels for On-Line Cognitive Assistance and Automation. In: Proceedings of NATO RTO Human Factors and Medicine Panel Symposium on Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures, La Coruna, Spain, 15-17 April 2002. Paper No 27. NATO Research and Technology Organisation, Neuilly-sur-Seine Cedex (In press).
- [9] Li, M. and Vitanyi, P. (1997). An Introduction to Kolmogorov Complexity and Its Applications, 2nd Edition. Springer, Verlag.
- [10] Fisher, R.A. (1925). Statistical Methods for Research Workers. Edinburgh.
- [11] Shannon, C.E and Weaver, W. (1949). The Mathematical Theory of Communication. University of Illinois Press.
- [12] Barber, K.S. and Martin, C.E. (1999). Agent Autonomy: Specification, Measurement, and Dynamic Adjustment. Proceedings of the Autonomy Control Software Workshop at Autonomous Agents, 8-15 May, Seattle, WA.
- [13] Barber, K.S., Goel, A. and Martin, C.E. (1999). The Motivation for Dynamic Adaptive Autonomy in Agent-Based Systems. University of Texas Report no. TR99-UTLIPS-AGENTS-02. Austin, Texas.
- [14] Thomas, M. (2003). Bayesian-Based Unmanned Underwater Vehicle Knowledge System: Scenario Definition, Application, Design and Implementation. QINETIQ/FST/CR035464. October. QinetiQ, Farnborough, Hants.
- [15] Water, M. and Taylor, R.M. (2004). Bayesian-Based Autonomous Decision Making in Unmanned Underwater Vehicles: Scenario Definition, Method Development, Implementation and Evaluation. DSTL/CR11773 V1.0. 07 October. Defence Science and Technology Laboratory, Farnborough, Hants.
- [16] Tansley, D.S.W. and Hayball, C.C. (1993). Knowledge Based Systems Analysis and Design. Prentice Hall.
- [17] Shadbolt, N.R. et al. (1999). Knowledge Engineering and Management. MIT Press.
- [18] Sanguesa, R. and Cortes, U. (1998). The Bayesian Agent: an incremental approach for learning agents working under uncertainty. Dept. of Software, Tech. Univ. Catalonia.

- [19] Anagnostopoulos, G.C. and Georgiopoulos, M. (2001). Ellipsoid ART and ARTMAP for unsupervised and supervised incremental Learning. University of Central Florida.
- [20] Johansson, C., Raicevic, P. and Lasner, A. (2002). Reinforcement Learning Based on a Bayesian Confidence Propagating Neural Network. Dept. of Numerical Analysis & Computing Science, Royal Institute of Technology, Sweden.
- [21] Wallace, C.S. and Freeman, P.R. (1987). Estimation and inference by compact coding. Journal of the Royal Statistical Society, 49(3):240-265.

Chapter 6 – ADVANCED UMV OPERATOR INTERFACES

Chapter Lead: M. Draper

Contributors: T. Barry, G. Calhoun, J. Clark, M. Draper, M. Goodrich, C. Jansen, J. Kessens, F. Kooi, A. Lefebvre, S. Murray, J. Nelson, C. Nielsen, G. Osga, A. Oudenhuijzen, M. Quigley, R. Shively, B. Simpson, R. Stone, L. van Breda, J. van Delft, J. van Erp

6.1 INTRODUCTION

Even with rapid advances in computer processing, automation technology, and artificial intelligence methods, there remains a critical need for human involvement in order for UMVs to successfully perform their missions. The human provides unique strategic and innovative decision-making capabilities within complex, dynamic, and time sensitive situations. UMV operator performance and, by extension, the UMV operator control/display interface, will be even more critical to achieving anticipated new and increasingly complex UMV capabilities including close-coupled operations with manned systems, UMV interoperability, and military strike/combat operations.

Given that humans are to remain a key component of UMV systems for the foreseeable future, it is important to recognize the unique challenges levied upon the operator. These challenges include the effects of system time delays (both fixed and variable), bandwidth limitations (which can be intermittent), datalink degradations/dropouts, and the loss of the rich supply of multi-sensory information often afforded to onboard operators. With future highly automated UMV systems, issues also include functional allocation of tasks between the operator and the system, human vigilance decrements, ‘clumsy automation’, limited system flexibility, mode awareness, trust/acceptance issues, failure detection, and automation biases. Additional challenges have been documented in detail elsewhere (Chapter 2). However, it is also important to note that the physical separation of crew from vehicle might also offer some unique benefits that should be exploited. Besides the obvious benefit to crew safety, it is quite likely that available bandwidth and the variety of available information sources might be, in certain cases, far greater for a geographically-separated UMV crew versus an onboard operator, potentially resulting in more situation awareness rather than less. This, of course, assumes that a well-designed operator interface exists that can rapidly filter and fuse this expanded information into intuitive displays, again underscoring the need to attend to operator interface issues to ensure maximal system performance.

It is also important to note that as technology advances, the role of the UMV operator must change as well. Therefore, UMV operator interfaces should not be considered ‘one-size-fits-all’, but must be tailored to match the capabilities and limitations of the host system and intended mission. Most current UMVs require that operators have the capability to manually control the vehicle and activate state changes (i.e., direct tele-operation). Thus, operator interfaces for these vehicles can best leverage the numerous lessons learned from decades of inner-loop control design research, while applying novel interfaces to combat challenges that are uniquely associated with UMV operation.

With new, highly automated UMVs, the operator’s role is becoming more supervisory in nature, overseeing the automated activation of programmed events (e.g., making sure the appropriate event is activated at the appropriate time), managing changes to the automated mission plan, and making more strategic-level decisions. These operator interfaces must take into account issues associated with automation management, including vigilance effects, brittle/clumsy automation, sudden workload spikes, etc.

Continuing this trend beyond the current state-of-the-art, a vision exists for a new interface paradigm for controlling next generation UUVs. This envisioned interface system involves multiple semi-autonomous UUVs being controlled by a single supervisor. These UUVs will have the capability to make certain higher-order decisions, independent of operator input and pre-defined mission plans. This capability of the UUV 'to decide' constitutes a whole new set of challenges for operators, as they will be required to rapidly judge the appropriateness of these decisions and assess their impact on overall mission objectives, priorities, etc. Future operator interfaces will need controls and displays tailored for multi-UUV control and must allow the operator the capability to easily inspect/override the autonomous UUV decision-making logic. These interfaces will also need to provide information fusing/filtering algorithms, intelligent prioritization/cueing logic, and possibly some form of adaptive task allocation in response to rapidly changing events and/or workload levels.

This chapter explores many relevant issues surrounding UUV control/display interface technology. The chapter begins with a discussion of the importance of pursuing a user-centered design methodology in designing UUV operator interfaces. This is followed by a section detailing available and applicable design guidelines as well as noticeable gaps in this area. Next, several candidate data input and display technologies are discussed in turn. Each technology section (with few exceptions) begins with a summary description of the technology area along with any commonly accepted subcategories of that technology. Next, there is a discussion of actual or potential application of the technology to UUVs. Lastly, technology maturity, challenges, and unresolved issues are summarized. The chapter then focuses on operator interface issues associated with multi-UUV supervisory control and concludes with additional UUV interface considerations such as scale, mobility, and various communication constraints.

6.2 USER-CENTERED DESIGN FOR UUV CONTROL

UUVs operating in collaborative, semi-autonomous groups represent a major advance in military capability. Multiple remote platforms conducting operations in hazardous environments – where errors can have serious military and political consequences – also represent a new level of engineering complexity. The missions planned for UUVs are diverse and complex by any standard; the control logic required to operate them will also be complex and will always contain an element of risk.

Because UUVs, like all military systems, are extensions of human intent, UUV effectiveness can only be as good as the clarity of that intent. That intent is conveyed via the primary tool for remote human control – the user interface. Good control depends on good information – which must be complete, sensible, reliable, and timely. The quality of the user interface, therefore, will ultimately determine the quality of system performance. A good interface can help the human controller to maintain situation awareness of the remote environment where UUVs are operating, can enhance goal setting under dynamic vehicle and mission conditions, and can optimize human analytical processes and decision-making.

Certainly, a lot is known about how to provide the human controller with good information and decision support tools – the challenge is to apply this knowledge aggressively and early in the design process. Human factors engineering (HFE) methods inform the interface design, i.e., its content, layout, and interaction metaphor, while human-system integration (HSI) methods place the interface in the context of the total human-UUV system including its missions, operating environment, and support requirements.

Human factors engineering defines the form and behavior of the controller interface. It applies knowledge of human perceptual capabilities, motor skills, memory capacity, decision-making processes and communication

styles to the design of interface functions. Complex applications involving teams of operators must also address human characteristics related to shared human goals, team interactions, and distributed decision-making. The primary objectives of HFE is to ensure that information presented to a controller matches their cognitive and decision-making requirements in real time, that the information is easily understood, and that controller decisions are easily implemented.

Human-system integration is a critical component of the systems engineering discipline that addresses human capabilities and limitations throughout the UMV development process. The objective of HSI is to match technology to user capabilities in order to optimize mission performance. HSI also employs HFE methods and data, but applies them to broader issues of safety, training, and to technology or mission evolution over the system life cycle. “Integration” implies a task conducted amid multiple, often-conflicting system design demands so HSI must address such issues as the impact of network communications architectures, varying levels of UMV automation capability (including intra-vehicle communications and decision-making), and the human role in coping with degraded conditions. HSI methods can ensure that systems are built to accommodate the characteristics of the personnel who will operate, maintain, and support them.

HFE and HSI tools and methods are highly complementary and, insofar as they reflect advocacy of the human role in system design, may be combined into an overarching concept of user-centered design (UCD). The UCD approach reflects an appreciation of human potential in the system engineering process. Regardless of the engineering sophistication of any military system, human controllers – with their unique abilities to sense and understand both the system and the mission – have always added the critical margin of performance that makes such systems viable. The UCD orientation to UMV development, therefore, represents a critical contribution to the success of such complex systems.

The new capabilities reflected by UMV systems will stress current engineering design practice regarding control logic, communications networks, and multi-level automation. These same capabilities will stress current perspectives of how human presence can best support the new missions and expanded mission modes enabled by UMVs. UCD, therefore, will be faced with new challenges that will extend our concepts of human-system interaction to settings where machines are cast (at a behavioral level) more as colleagues/collaborators than as mere tools in military operations:

- New models of human-machine and human-human communication must be elaborated, especially in the context of network-centric warfare doctrine.
- New approaches to smoothly and safely altering multi-agent control configurations (the consequence of enhanced automation capabilities) must be defined.
- Because UMV control should be achievable anywhere – from the fixed-base command center to the mobile, individual warfighter – scaleable interface designs, based on formal HFE/HSI principles, must be generated.
- As hardware and mission concepts change over time, UCD methods must accommodate the certain requirement for graceful (rather than disruptive) life cycle evolution.
- Finally, new testing and validation methods must be generated and proven to ensure that the resulting systems will perform as required.

UCD has a clear and historically proven role in good system design. Furthermore, when explicitly included at the beginning of a sound systems engineering program, UCD can be accommodated without interference to other engineering tasks. While UMV system design must address new challenges across a broad front of engineering specialties, UCD integration is an enhancing – rather than distracting – step in such an ambitious

undertaking. An irony of many military acquisition programs is that UCD is never deleted; some consideration to HFE and HSI issues is almost invariably required either at the time of system fielding or shortly thereafter, when performance problems force an examination of the human role in mission effectiveness – usually with increased cost or delay. UMV design can expand both our engineering and human interface design knowledge, and can add to the technical “toolboxes” of both domains. To realize the full potential of the UMV concept, however, UCD design methods must be fundamental to the engineering process from its initiation.

6.3 GUIDELINES AND GAPS

Since the advent of highly capable uninhabited vehicles, notably in the application domains of defence, offshore oil and gas exploration, attention has increasingly focused on the development of technologies necessary to endow vehicles with complete autonomy. This approach has not met with widespread success. Evidence frequently points to the fact that the human operator still has a significant role to play in the future of uninhabited vehicles, as part of a control continuum that ranges from direct tele-operation during critical mission phases and recovery modes to the high-level supervision of single or multiple platforms. However, few (if any) usable guidelines and/or experimental test beds exist to help ensure that human factors issues are taken into account early in the design lifecycle of uninhabited vehicles and their control-display interfaces with the human operator or supervisor.

6.3.1 Pre-Requisites to Selecting Human Interface Devices

The market for off-the-shelf interface devices worthy of consideration for UMV application is rapidly growing. In particular, the exploitation of games console hand controller designs is gaining pace, as there is a perception (unproven at the time of writing) that new recruits to the Armed Forces will adapt “seamlessly” to advanced military interfaces if those interfaces are based on familiar gaming devices. Despite this, an early human-centred design approach to device specification/design/procurement is essential; any display or control device must be selected on the basis of a thorough review of the tasks expected of the human operator, regardless of whether his/her role is that of flight/mission/payload specialist, supervisor or field dispatch (see Section 6.2).

The pitfalls of being swayed by technology push are now well documented throughout the international human factors community. Obsolete and unused Virtual Environment Centres bear witness to the hazards of selecting technologies before the needs of the end user population have been fully understood. Yet still one finds examples where, whilst the information to be displayed to the human user has been subjected to strong human factors principles, those same principles are ignored in what is blatantly a prescriptive selection of unproven human interface technologies. This situation is particularly rife in the virtual reality/multi-sensory interface arena. Here, advanced display techniques are often adopted only as a result of their “high-tech” qualities. However, when implemented in a tele-operation or telepresence system, those same qualities could then limit the utility of the system, because the human user spends more time trying to adapt to the limitations of the interface technology, rather than benefiting from the displayed content of the application itself.

To overcome this problem, the interactive facilities for UMV supervision and control must evolve from the early performance of a hierarchical task analysis (at least), and a domain-specific analysis (at best; e.g., [1]). The interactive facilities must also take into consideration the domain-specific issues covered by the task analysis (and the subject of Static/Dynamic Allocation of Function specifically (e.g., [2,3,4,5]) and must take into consideration the human factors limitations of candidate interface technologies (e.g., [1]).

6.3.2 Standards/Methodologies/Best Practice and Gaps

Academic and military laboratory-based RandD programmes have often failed to generate realistic interface design guidelines to support the human operator in controlling UMVs safely and efficiently. Furthermore, the international standards community also admits that, as far as advanced computer-based human interfaces are concerned, it is further behind in the delivery of underpinning standards for new technological developments, such as unmanned systems, than it would like to be.

There have been a few attempts historically to collate information of relevance to the hazardous environment tele-operation community. As well as a highly relevant Oak Ridge publication [6], UK research in the early 1980s led to the production of a Human Factors Design Handbook [7]. This handbook was specifically concerned with the design of human interfaces for Remotely Operated (submersible) Vehicles (ROVs) for the North Sea oil and gas industry and was used to design consoles for some vehicles still in service today. Whilst, today, this document is somewhat out of date (especially with regard to informational displays and the combination of video images with alphanumeric data or forms of symbology to assist in navigation), it still contains some information of relevance to general ergonomics practice, workplace and hand control design.

Another report that was produced with remote operations in mind focused on the needs of the nuclear industry and developments in support of mobile and manipulator systems for irradiated facilities [8]. Again, some of the information is dated. However, sections on hand control design and the application of recent (1990s) interactive technologies (e.g., from the virtual environments community) are still relevant.

More recently, organisations have been active in promoting the need to collate human factors information of relevance to the unmanned or remotely operated vehicle arena. A publication [9] was written to fulfil the role of an informative annex to pre-contractual and contractual documents relating to the design of future military or explosive ordnance disposal (EOD) tele-operated/robot systems.

For the foreseeable future, then, tele-operated vehicle and manipulator system designers will have to rely on general ergonomics and human factors texts, as adopted by the civilian and military human factors community. This is far from satisfactory because such texts tend to be outdated before they are even published. A good example here is the current generation of ISO standards pertaining to human-computer interaction, such as ISO 14915, which does not adequately address the needs of the growing multi-modal and synthetic environments communities. Furthermore, the refresh cycles for these documents are very long-term indeed. Some standards, such as DEF STAN 00-25 in the UK (*Human Factors for Designers of Equipment*) are only now being considered for updating (or “future proofing”) – many of the contents dating back to, for example, [10].

Ageing and irrelevant contents of existing texts also force the authors of contemporary standards and guidelines to take short cuts when attempting to make their documents relevant to a particular domain or system. One notable example of this is Appendix B3 (Human Computer Interface) of STANAG 4586 – *Standard Interface of the Unmanned Control System (UCS) for NATO UAV Interoperability*. Here, the absence of any appropriately packaged knowledge relevant to UMV human interface design (and relevant knowledge certainly exists in the UMV community), has forced the authors to use unmodified extracts from ISO 9241 – *Ergonomic Requirements for Office Work with Visual Display Terminals*.

At a very high level, then, the human-system interfaces provided as part of an integrated UMV system, regardless of the environment on which that vehicle is to be deployed (land, air, sea surface, subsea, space, etc.) must, at their most basic level, be capable of:

ADVANCED UMV OPERATOR INTERFACES

- Presenting the operator with appropriate (video and/or synthetic) imagery from the remote environment to enable situation awareness, waypoint planning, real-time control (driving, flying, etc.), obstacle avoidance (including friendly forces or civilians), payload selection, payload operation and general manipulation to occur safely and efficiently;
- Presenting the operator with appropriate real-time data to enable him/her to transition seamlessly between supervisory and tele-operation modes of control without significant loss of situation awareness (encompassing the status of both the vehicle – power, performance, command link integrity, “health” and other subsystems – and the remote environment);
- Providing the operator with control and data input devices appropriate for remote control, manipulation, subsystem and payload selection/operation tasks; and
- Presenting the human operator with mission-specific data, adopting formats that avoid any cognitive conflict or mental resource monopolisation, thereby compromising real-time control or supervision.

These presentational requirements must not be hindered in any way by the selection and/or design of the human interface hardware, and displays and controls must support the human operator’s intuitive exploitation of the information he/she is provided. More detailed design principles and guidelines, including reference to the development of UMV workstations and portable consoles (originally written in support of human interface design for unmanned EOD vehicles) can be found in [9].

Where appropriate, and in the absence of access to physical UMV assets or appropriate deployment scenarios, Virtual or Synthetic Environment (VE/SE) test beds should be given serious consideration in the quest to fill the human factors knowledge gaps in both interface technology provision and in the definition of the role of the human operator in supervising or directly controlling one or more UMV systems. Early examples of such test beds, based on low-cost approaches to simulation (e.g., using Microsoft DirectX, .NET or games engine technologies) are available. The *Alchemy* experimentation system, for example, developed as part of the UK Human Factors Integration Defence Technology Centre programme, supports Human Factors investigations of advanced display and control devices for UMV interaction, from head-mounted displays to video console-like hand controllers [11]. *Alchemy 2* (Figure 6-1), the latest version of this test bed, has evolved from a programming-intensive environment to become a highly reconfigurable “serious gaming” implementation and has already been demonstrated in the context of an iSTAR UAV (Allied Aerospace) and “marsupial” (SPAWAR) land vehicle deployment (tele-operated), together with a new man-portable, twin turbofan UAV concept (Kestrel Aerospace, UK).



Figure 6-1: Alchemy 2 Experimentation System.

6.3.3 References for Guidelines and Gaps

- [1] Stone, R.J. (2004). “Rapid Assessment of Tasks and Context (RATaC) for Technology-Based Training”. Proceedings of I/ITSEC 2004, Orlando.
- [2] Rouse, W.B. (1977a). “Human Interaction with an Intelligent Computer in Multi-Task Situations”. Proceedings of the 11th Annual Conference on Manual Control, NASA Ames Research Centre, pp. 130-143.
- [3] Rouse, W.B. (1977b). “Human-Computer Interaction in Multitask Situations”. IEEE Transactions on Systems, Man, and Cybernetics; 7(5), pp. 384-392.
- [4] Rieger, C.A. and Greenstein, J.S. (1982). “The Allocation of Tasks between Human and Computer in Automated Systems”. Proceedings of International Conference on Cybernetics and Society; Seattle, Washington, IEEE, 204-208.
- [5] Milgram, P., Van De Graaf, R.C. and Wewerinke, P.H. (1985). “Control Loops With Human Operators in Space Operations – Part 1: Human Engineering Analysis, Synthesis and Evaluation Techniques”. National Aerospace Laboratory, The Netherlands; NLR TR 84116 L, Part 1.
- [6] Draper, J.V. (1985). “The Human-Machine Interface in Mobile Teleoperators”. Proceedings of the Department of Energy Workshop on Requirements for Mobile Teleoperators for Radiological Emergency Response and Recovery (Foltman, A.J., Ed.). Dallas, TX: Argonne National Laboratory.
- [7] Stone, R.J., Day, P.O., Rogers, H.G. and Kelly, C.J. (1984). “ROV Workstation Design Handbook”. UK Department of Energy Contract No. E/5B/CON/753/802. Unpublished British Aerospace Document Ref. JS10014.
- [8] Stone, R.J. (1992). “British Nuclear Fuels Limited Agreement No. A022595 (Schedule 2): Natural Man-Machine Interface Study Final Report, Volume 1 – Review and Requirements”. Advanced Robotics Research Limited (ARRL) Report No. ARRL.92 002.
- [9] Stone, R.J. (2002). “Human-System Interfaces for EOD Telerobots: Introduction to Human Factors Design Guidelines”. Unpublished report prepared under contract to the QinetiQ Centre for Robotics and Machine Vision (Contract No. C4004-20747).
- [10] Van Cott, H.P. and Kinkade, R.G. (Eds., 1972). Human Engineering Guide to Equipment Design. New York: McGraw-Hill Book Company.
- [11] Stone, R.J. (2005). “Project Alchemy: An Experimental Human Factors Test Bed for iSTAR UAVs in Urban Operations”. Proceedings of HCII 2005; Las Vegas.

6.4 DATA INPUT TECHNOLOGIES

6.4.1 Manual Input Devices (keyboards, mice, control sticks, touch devices, etc.)

6.4.1.1 Description of Technology

Controllers that involve a manual input include single-purpose buttons, levers, and joysticks as well as a keyboard for text entry and a mouse for pointing and selecting text and icons presented on a display.

Trackballs and touch pads can also perform much the same function as a mouse. Since these control devices are commonly used in a variety of applications, no further description will be given herein. A less frequently employed manual control device employs touch sensitive technology in which operators press the display surface over the appropriate label or icon presented on a display to make a selection. A directory of manufacturers of touch screen devices is available [1].

Touch sensitive displays can sense that the display is being touched by a pen or finger and can send this information, along with the touch location, to a host controlling system. A variety of technologies have been employed to implement touch screens: resistance, optical, capacitive, and acoustic techniques [2]. These technologies can be grouped into two classes: touch screens that use an overlay that responds to pressure and screens that are activated when the finger or pointer interrupts a signal. All implementations are considered robust and operation is simple and easy to learn. As a more “direct” selection input method, a mechanical intermediary (mouse) is not needed; nor is there need for positional feedback (cursor) consuming display space. Rather, the touch screen serves as both an input and output device, capitalizing on direct eye-hand coordination.

6.4.1.2 Actual or Potential Applications to U MVs

In existing U MV control stations, operators typically employ the manual control devices just described, with the exception of the touch screens. There is, however, potential U MV applications of touch screens, especially in future supervisory control stations that feature more automated control of vehicle and camera movement. Since the operator will have less dedicated hands-on (e.g., stick and throttle) control in these stations, the majority of operator interaction will involve monitor and control of subsystems. Thus, touch screens have a potential application to these U MV stations, as function selection using touch screens has proven to be fast and accurate, as well as easy to learn in other ground-based applications [3]. Moreover, since the number, shape, size, location, and label of the touch-sensitive fields are under software control (compared to electromechanical controls), they can be easily reconfigured corresponding to periodic upgrades made in the U MV system control architecture. It should be noted, though, that touch screens are only appropriate when inputs are limited and well defined [4]. Touch screens are not suited for tasks requiring precise positioning such as drawing and graphical input. Additional guidelines on the design of touch screens (touch-selection strategies, button size, feedback strategies, mouse-emulation strategies, touch biases screen angles [5] and numeric keypads [6]) are available for use in applying touch screens for U MV stations.

6.4.1.3 Technology Maturity, Challenges, and Unresolved Issues

In that manual control devices have historically been used in U MV ground control stations, technology maturity is not an issue. Even touch screens are commercially available and widely used in banks, restaurants, airports, and ground-based command/control stations. Thus, a Technology Readiness Level (TRL) Rating #6 can be assigned to touch screens, since this input device has been demonstrated in relevant environments. (Conventional manual devices are at a TRL Rating #9.) Even though touch screens and other manual devices are appropriate for U MV station applications, there still remain challenges in determining how best to employ these devices in future supervisory stations such that the controls support decision making or execution in a timely and error-free manner.

Dedicated (single-function) manual control devices need to be easily located, grasped, and manipulated. All the information and control devices needed for a particular set of activities should be in close proximity and ideally available with less than two key presses. Proper and consistent formats, abbreviations, symbol meaning, control assignments, procedures and rapid (< 0.2 seconds) feedback need to be employed so the action required and status of control operation is intuitive to the operator [7].

Human-engineered design of multi-function controls is also needed [8]. With multi-function controls, operators select menu options presented on a control station display using buttons on the periphery of the display or a touch sensitive screen. While a large number of systems can be controlled via one control device, there is a danger in the operator spending excessive time with the head down in order to progress through multiple interface layers or menus. This can lead to distraction from the primary tasks of maintaining situation awareness and supervising UMV control. Besides effective labelling so the function associated with each switch is obvious, navigation between the menus and the interactive sequences need to be efficient.

Function selection using touch screens presents additional challenges. Arm fatigue and screen obstruction by the hand may occur. This is especially true with pen input, along with the hassle of having to pick up the fragile pen for each input. Operators must be more attentive to visual and audio feedback due to the lack of kinesthetic feedback associated with manipulating real switches and knobs [9]. Given the size of an operator's finger/pointer and the parallax potential of the screen, selection of small targets or closely spaced functions is also difficult. There are also limits on the types of interactions that can be accomplished. For instance, selecting and dragging objects, inputting precise positioning, rubber band line drawing, pop up menu selections and other interactions for which the mouse is well adapted are not suited for touch screen operation. To enable these more complex interactions, the touch screen needs to sense the degree, or pressure, of contact or sense multiple points of contact, besides just sensing the push and release of touch. If the system isn't able to sense at least two levels of pressure, then auxiliary devices must be used for signalling [9]. One potential solution is to use different sensor densities which allow the creation of display areas with different resolutions [10].

6.4.1.4 References for Manual Input Devices

- [1] Buxton, B. (2005). A directory of sources for input technologies. Available at: <http://www.billbuxton.com/InputSources.html#anchor693936>
- [2] Bullinger, H.-J., Kern, P. and Braun, M. (1997). Controls. In: Salvendy (Ed), Handbook of Human Factors and Ergonomics, 2nd Edition, New York: John Wiley and Sons, Chapter 21, pp. 729-771.
- [3] Sears, A. and Shneiderman, B. (1991). High precision touch screens: Design strategies and comparisons with a mouse, International Journal of Man-Machine Studies, 34, 593-613.
- [4] Plaisant, C. and Sears, A. (1993). Touchscreen interfaces for alphanumeric data entry. In: B. Shneiderman, Ed., Sparks of Innovation in Human-Computer-Interaction. Norwood, NJ: Ablex.
- [5] Scott, B.M. and Conzola, V. (1997). Designing touch screen numeric keypads: effects of finger size, key size, and key spacing. Proceedings of the Human Factors and Ergonomics Society, 360-364.
- [6] Lewis, J.R. (1993). Literature review of touch-screen research from 1980 to 1992. IBM Technical Report 54.694. New York: IBM Corporation. Available at: <http://drjim.0catch.com/touchtr.pdf#search='Beringer%20AND%20touch%20and%20input>
- [7] Lind, J.H. and Burge, C.G. (1992). Human Factors Problems for Aircrew-aircraft Interfaces: Where should we focus our efforts? In "Advanced Aircraft Interfaces: The Machine Side of the Man-Machine Interface", AGARD-CP-521, 3-1-3-12.
- [8] Calhoun, G.L. and Herron, E.L. (1982). Pilot-machine Interface Considerations for Advanced Aircraft Avionics Systems, In: "Advanced Avionics and the Military Aircraft Man/Machine Interface", AGARD-CP-329, Chapter 24, 1-7.

- [9] Buxton, W., Hill, R. and Rowley, P. (1987). Issues and Techniques in Touch-sensitive Tablet Input, *Computer Graphic*, 19(3), 215-224.
- [10] Westerman, W., Elias, J.G. and Hedge, A. (2001). Multi-touch: A new tactile 2-D gesture interface for human computer interaction. *Proceedings of the Human Factors and Ergonomics Society*, 632-636.

6.4.2 Speech Recognition Systems

6.4.2.1 Description of Technology

Automatic Speech Recognition (ASR) technology, which transforms an operator's spoken words into machine text, has been around for over 50 years [1]. Investigating this technology for use in military systems has been ongoing for over 30 years. In the early 1970s, researchers quickly realized that along with the rapidly advancing computer technology came the equally rapid proliferation of knobs, dials, switches and other traditional interface devices needed by operators to control that technology. Not only would these conventional controls begin to take up large amounts of physical space, but their sheer numbers would also quickly overwhelm the human operator's ability to effectively manage them all, especially in time critical situations. For these reasons, researchers began to explore the possibilities of using ASR, also known as Direct Voice Input (DVI), in addition to speech synthesis technology, which translates text into machine-spoken words, to control and display information [2,3,4].

Much of the early research in the military use of speech recognition technology was applied to the single-seat aircraft cockpit [5,6,7,8,9] where pilots must not only use stick, throttle and rudders to keep the aircraft in the air, but must also manage an increasing number of sophisticated onboard computer systems for offensive, defensive, surveillance, and a myriad of other tasks. It was becoming increasingly clear that without another crewmember in the cockpit, the complexity of these systems would eventually overwhelm the single pilot's ability to effectively manage the system. If an accurate DVI system were used, the pilot could verbally ask the aircraft to accomplish simple tasks like changing a radio frequency or navigate to a new waypoint [10,11]; much the same way a pilot might ask his/her co-pilot to accomplish these tasks.

Since 1987, the United States Defense Advanced Research Projects Agency (DARPA) and the National Institute of Standards and Technology (NIST), have sponsored objective benchmark tests in the DVI research community [12]. Figure 6-2 shows how the state of the art of the technology has improved significantly in recent years, and as a result, is rapidly becoming widely accepted by users [13].

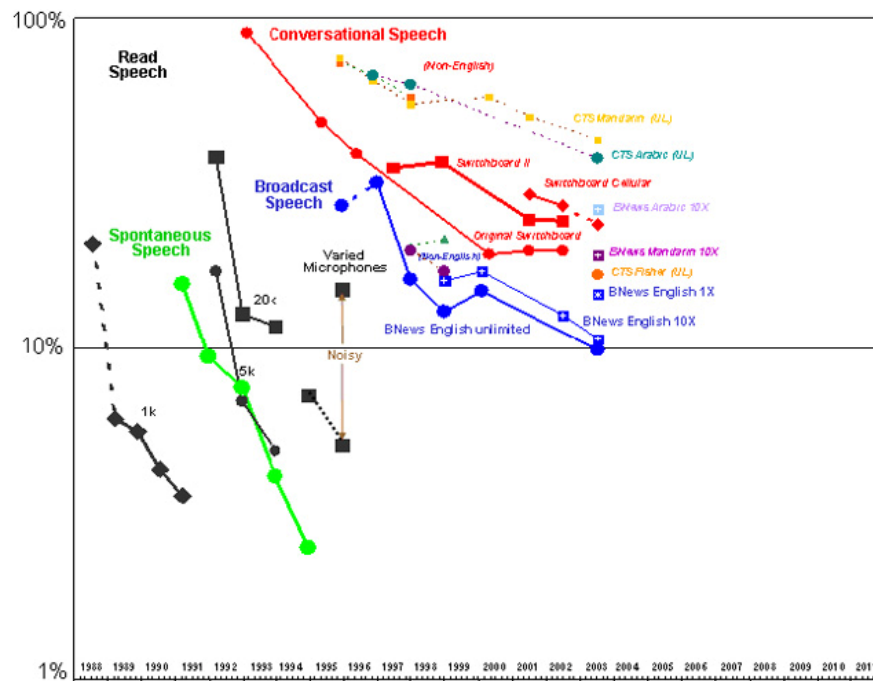


Figure 6-2: NIST Speech Recognition Benchmark Test History.

Speaker dependent, discrete word recognition systems requiring users to repeat all vocabulary words and phrases numerous times before ever using the system have given way to speaker independent, continuous speech systems requiring no prior system training. Small, static vocabularies of 300 or less words have been replaced by very large, dynamic vocabularies containing tens of thousands of words and are robust enough to handle both male and female native and non-native speakers. The systems have also matured to the point where they can achieve high recognition rates in very noisy environments [14,15]. As a result of these recent technology advances, numerous military applications for using this natural and intuitive communication method are being pursued [16,17,18,19,20].

6.4.2.2 Actual or Potential Applications to UMVs

Numerous laboratory and field studies have shown that the intelligent use of speech recognition and synthesis technology can significantly improve the operator interface. In an aircraft simulation experiment using DVI to control single-seat cockpit functions [10], speech was found to be a viable control method for changing radio frequencies and navigation coordinates and for designating ground targets in an air attack mission. Using this technology, data entry task performance was increased, while overall pilot workload was reduced. When multi-tasking, pilots were able to enter numeric data into the onboard systems while their hands and eyes were busy. In addition, the interaction of using speech technology combined with an automatic target cuing system resulted in superior performance in selecting and marking targets.

In a study designed to compare data entry performance using speech recognition with manual (keyboard, mouse, push button) methods [17], pilots performed data entry and query tasks while flying a simulated Unmanned Aerial Vehicle mission. The operators were asked to perform a continuous flight/navigation control task while responding to intermittent data entry, data query and emergency checklist tasks. The results showed that data entry task performance improved approximately 40% when pilots used DVI, in comparison

to performance with conventional manual controls. The operators also judged the speech system to be easier to use than manual controls and resulting in lower workload.

The U.S. Army has also investigated the use of speech recognition technology for ground vehicle operator interfaces in a M1A2 tank simulator [21]. Results showed that tank commanders could perform tasks (such as calls for fire, medical evacuation requests and radio setup) faster using speech input compared to using conventional push buttons and a joystick cursor controller. Operators could eliminate the menu “drill-down” search for the “call for fire” menu function by simply speaking a “call for fire” command. Operators also reported higher perceived levels of workload when using the conventional input method.

Quite a bit of research in the potential uses for speech recognition technology in helicopters has been done in the United States [22,23,24], United Kingdom [16] and Canada [25,26] including a successful flight test of an ITT system in the mid and late 1980s. Successful applications of speech technology in a number of ground based helicopter simulation platforms as well as a number of actual helicopter flight tests in the United Kingdom, Canada and the United States are described in [16,26].

Interesting uses for speech recognition technology for training systems have also been fielded by the U.S. Naval Air Warfare Center Training Systems Division (NAWCTSD) in Orlando, Florida. Some systems already in operational use include:

- A Carrier Air Traffic Control Center (CATCC) laboratory which realistically simulates the at-sea air traffic control environment. A speech recognition system replaces human pilot role players at the CATCC “C School”, an advanced technical training facility in Pensacola, Florida that serves 90 Navy students per year plus team training for each of the Navy’s carriers.
- A Tower Operated Training System (TOTS) laboratory, also in Pensacola, Florida, serves as a VFR Tower Air Traffic Control facility trainer that simulates the visual environment of a tower cab. TOTS features speech recognition/synthesis to enable direct student interaction with simulated pilots.
- The Navy’s Advanced Radar Air Traffic Control (ARATC) trainer in Pensacola, Florida, realistically simulates shore-based air search and ATC radar systems using speech recognition/synthesis technology. The trainer provides for approach, arrival and precision radar final approach training by allowing students to communicate with simulated pilots.
- The Radar Air Traffic Control Labs (Radlabs) training system in Pensacola uses speech recognition to teach basic radar air traffic control procedures.
- The Amphibious Air Traffic Control Center (AATCC), a realistic trainer for the amphibious assault ship environment, uses speech recognition/synthesis to provide realistic interaction with the simulated pilots.
- A Landing Signal Officer (LSO) Trainer at Naval Air Station, Oceana, Virginia features a wide field-of-view projection of a carrier landing platform and allows the LSO student to communicate with the pseudo-pilot via a speech recognition/synthesis system.
- The Air Traffic Control Proficiency Trainer (APTS) is a table-top low cost trainer developed to train basic aircraft control and phraseology. APTS recently was delivered to 46 U.S. Navy and Marine Corps sites worldwide.

It is clear from the number of successful applications of this technology in both simulated and operational ground and flying platforms that speech recognition will be an important and integral component in future military operator interfaces. Indeed, operational use of the technology has already found its way into military

jet aircraft. In Europe's newest jet fighter aircraft, the Typhoon, DVI gives pilots the ability to control data entry functions such as changing radio frequency and displaying fuel status as well as more critical functions such as configuring radars and radios, all without having to move their hands from the flight controls. This DVI functionality serves as an alternative to using manual control methods when the pilot's hands and eyes are busy.

Following the Typhoon's lead, the new French Rafale aircraft will have a DVI capability, allowing the pilot to perform actions through spoken commands using a vocabulary of 90 to 300 words. The United States also plans to field a DVI capability in its new Joint Strike Fighter (JSF). Under a Memorandum of Agreement signed with the JSF prime contractor Lockheed Martin, Adacel (Melbourne, Australia-based) will develop a speech-enabled cockpit control system as part of the 10-year System Development and Demonstration phase of the JSF program.

Through the breadth of DVI research conducted since the 1950's, a number of "lessons learned" have emerged that serve, in part, as suggested guidelines for the successful implementation of this technology. These lessons, together with general guidelines published by Gardner-Bonneau, Rudnický and others for telephony and other spoken language systems [13,27] should serve as a baseline set of guidelines for the successful implementation of speech recognition technology in military systems. Some of these include:

- Limit or eliminate speaker training – State of the art speech recognition systems no longer require speakers to "train" the system to recognize their voice commands. Modern DVI systems automatically adapt to the ambient acoustical environment and the nuances of a speaker's voice over time.
- Phrases that are from three words or longer are more distinctive and will be better recognized than short one or two word phrases. Military operators are trained to use short, terse speech on radios, but single-word commands are less distinctive and can be confused by the recognizer.
- Avoid commands that sound similar, but have different meanings. For example, "Turn backups on" and "Turn backups off" differ by only one phoneme and might be confused by the recognizer in a noisy environment.
- Define commands that are easy to remember, feel natural to say, and don't conflict with menu items or controls.
- Make use of "Macro" commands. Provide speech-recognition commands that add value by doing more than can be accomplished through a single click or keyboard equivalent.
- Use confirmation when necessary. For commands that could result in data loss, ask for confirmation before executing the command.
- Redundancy – Make every attempt to provide an alternative method for accomplishing an action. Don't make speech the only way for the user to accomplish a task.
- Errors will occur. Bias toward deletion errors, rather than errors of insertion or substitution.
- Have a clear understanding of the trade offs associated with using speech controls vs. manual controls and limit the use of speech for critical tasks that could be accomplished with a simple button push.
- Provide feedback to the user to indicate that the speech system either took or didn't take action.
- If graphic feedback is impractical, provide auditory feedback.
- At all times, the user should know what can be spoken.

- Do not overwhelm the user with feedback.
- A robust, continuous listening system is ultimately better than one that requires explicit user action. Unfortunately, in many military systems, due to high ambient background noise and/or other speakers in close proximity, a push-to-talk implementation is probably the best solution (push and hold a button to speak, release when done speaking).
- Offer an Undo capability. If Undo is not practical, use a confirmation protocol in cases where undoing a recognition error is troublesome.
- More complex applications need to track state, so that actions are interpreted in the proper context.
- Out-of-Phraseology Speech – Speech recognizers are not yet capable of understanding unconstrained human speech. Accordingly, applications are developed based on constrained vocabularies – but users often say words that are not in the legal vocabulary. Since the speech recognizer will try to make the best match, undetected out-of-phraseology speech could be processed with chaotic results. The challenge is to detect out-of-phraseology speech and reject it before it is post-processed.
- If a certain action is made available through speech, make sure that tasks involving this action can be completed via speech. If confirmation is required, make sure the user can speak the response (instead of forcing the user to type something, for example). Users prefer to stay in one input mode rather than switching back and forth depending on the task.

6.4.2.3 Technology Maturity, Challenges, and Unresolved Issues

Speech recognition and synthesis technology has already been fielded in military training and simulation systems using relatively small vocabularies. System prototypes have also been successfully demonstrated in operational environments such as aircraft cockpits and ground control stations, and are considered to be at TRL Rating #7. However, the ultimate goal of speech technology researchers is to create a system that listens, understands and behaves as well as (or better than) a human might in the same circumstances. Current state of the art systems are quite good at listening for predefined words and phrases, but are not yet very good at understanding unconstrained, natural language speech. Significant research in machine language understanding is currently being done for both commercial and military systems. The U.S. Defense Advanced Research Projects Agency (DARPA) has funded much of this work under their Communicator and other programs. Several leading universities have built variations of the Communicator architecture, including MIT's Galaxy Communicator system [28], Carnegie Mellon University's (CMU) Communicator system [29], and the University of Colorado's CU Communicator system [30].

6.4.2.4 References for Speech Technology

- [1] Davis, K.H., Biddulph, R. and Balashek, S. (1952). Automatic Recognition of Spoken Digits, *Journal of the Acoustical Society of America*, 24 (6), 637-642.
- [2] Beckett, P. (1987). Voice Control of Cockpit Systems. In: *Information Management and Decision Making in Advanced Airborne Weapon Systems: Conference Proceedings of the Aerospace Medical Panel Symposium*. Toronto, Canada, 27, 1-27.
- [3] Werkowitz, E.B. (1984). Speech Recognition in the Tactical Environment: The AFTI/F-16 Voice Command Flight Test. In: *Proceedings of Speech Tech '84 Voice Input/Output Applications Show and Conference*, New York, NY.

- [4] Lizza, G. and Goulet, C. (1986). Cockpit Natural Language. Proceedings of the 1986 National Aerospace and Electronics Conference. Dayton, OH: IEEE, 818-819.
- [5] Barry, T., Liggett, K. and Williamson, D. (1997). Human-Electronic Crew Communication: Applications for Speech Recognition in the Cockpit. AFRL-HE-WP-TR-1999-0235. The Human-Electronic Crew: The Right Stuff? Tri-National Workshop Proceedings, Kreuth, Germany, 123-129.
- [6] Gerlach, M. and Onken, R. (1993). A Dialogue Manager as an Interface between Aircraft Pilots and a Pilot Assistant System. In: Human Computer Interaction, Proceedings of Fifth International Conference on HCI (HCI International '93), Salvendy G. and Smith M.J. Eds., 98-103, Volume 2.
- [7] Onken, R. (1995). Human-centered Cockpit Design Through the Knowledge-Based Cockpit Assistant CASSY, Paper presented at AGARD Symposium on Situational Awareness, DRG Panel 8, Technical Proceedings AC/243 (Panel 8), TP/7, AGARD/NATO Publication.
- [8] South, A. (1997). Voice Recognition in Adverse Aircraft Cockpit Environments. In: Audio Effectiveness in Aviation, AGARD Conference Proceedings 596. AGARD-CP-596, p. 34-1.
- [9] Steeneken, H. and Pijpers, E. (1997). Development and Performance of a Cockpit Control System Operated by Voice. In: Audio Effectiveness in Aviation, AGARD Conference Proceedings 596. AGARD-CP-596, pp. 33-1.
- [10] Barbato, G. (1999). Lessons Learned: Integrating Voice Recognition and Automatic target Cueing Symbolology for Fighter Attack Missions. Tenth International Symposium on Aviation Psychology, Columbus, OH.
- [11] Williamson, D. and Barry, T. (1990). Cockpit Application of Voice Technology. Proceedings of the Eleventh Annual IEEE/AESS Dayton Chapter Symposium, IEEE, Dayton, OH, 57-60.
- [12] Pallett, D.S. (2003). A Look at NIST's Benchmark ASR Tests: Past, Present, and Future, National Institute of Standards, http://www.nist.gov/speech/history/pdf/NIST_benchmark_ASRtests_2003.pdf
- [13] Gardner-Bonneau, D.J., Ed. (1999). Human factors and voice interactive systems. Boston, MA: Kluwer Academic Publishers.
- [14] Williamson, D., Barry, T. and Liggett, K. (1996). Flight Test Performance Optimization of ITT VRS-1290 Speech Recognition System. In: Audio Effectiveness in Aviation: Conference Proceedings of the Aerospace Medical Panel Symposium, Copenhagen, Denmark, p. 35.
- [15] Williamson, D., Barry, T. and Liggett, K. (1996). Flight Test Results of ITT-1290 in NASA OV-10. Proceedings of the 15th Annual International Voice Technologies Applications Conference (AVIOS '96), San Jose, CA, 335-345.
- [16] Collins, P., McKelvy, T. and Abbott, M. (2004). Mature Speech Recognition Technology for Military Helicopters. Paper presented to the American Helicopter Society 60th Annual Forum, Baltimore, MD.
- [17] Draper, M., Calhoun, G., Ruff, H., Williamson, D. and Barry, T. (2003). Manual versus Speech Input for Unmanned Aerial Vehicle Control Station Operations. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, Denver, CO: HFES.

- [18] Williamson, D. and Barry, T. (2001). Speech Recognition in the Joint Air Operations Center – A Human-Centered Approach. Proceedings of the 9th International Conference on Human-Computer Interaction, New Orleans, LA.
- [19] Williamson, D. and Barry, T. (2000). The Design and Evaluation of a Speech Interface for Generation of Air Tasking Orders. Proceedings of the Human Factors and Ergonomics Society 44th Annual Meeting, San Diego, CA, 750-753.
- [20] Williamson, D., Barry, T. and Draper, M. (2004). Commercial Speech Recognition Technology in the Military Domain: Results of Two Recent Research Efforts. Proceedings of the 23rd Annual Applied Voice Input/Output Society (AVIOS) Conference, San Francisco, CA.
- [21] Gross, J., Ciappara, N., Smist, T. and Benson, P. (1998). Evaluating the M1A2 Tank Commander's Interface: The Battle of Input Devices. Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting. Chicago, IL: HFES.
- [22] Holden, J.M., Stewart, S.J. and Vensko, G. (1987). Speech Recognition in a Helicopter Environment. Proceedings of Military Speech Tech '87. Arlington, VA: Media Dimensions, 147-152.
- [23] Holden, J.M. (1989). Two Helicopter Flight Tests of Voice Command. Proceedings of Military Speech Tech '89. Arlington, VA: Media Dimensions.
- [24] Simpson, C. (1990). Evaluation of Speech Recognizers for Use in Advanced Combat Helicopter Crew Station Research and Development. NASA Technical Memorandum 90-A-001, Moffett Field, CA: Ames Research Center.
- [25] Farrell, P., Churchill, L., Wellwood, M. and Herdman, C. (2001). Integrating Direct Voice Input in a helicopter crew environment. Proceedings of the 11th International Symposium on Aviation Psychology, Columbus, OH: OSU.
- [26] Swail, C. and Kobieski, R. (1997). Speech recognition in the Helicopter Cockpit Environment. American Helicopter Society 53rd Annual Forum, Virginia Beach, VA.
- [27] Rudnicky, A. Speech Interface Guidelines. <http://www.speech.cs.cmu.edu/air/papers/SpInGuidelines/SpInGuidelines.html>
- [28] Polifroni, J. and Seneff, S. (2000). Galaxy-II as an Architecture for Spoken Dialogue Evaluation, Proceedings of the Second International Conference on Language Resources and Evaluation (LREC), Athens, Greece.
- [29] Rudnicky, A., Thayer, E., Constantinides, P., Tchou, C., Shern, R., Lenzo, K., Xu, W. and Oh, A. (1999). Creating natural dialogs in the Carnegie Mellon Communicator system. Proceedings of Eurospeech, 1531-1534.
- [30] Pellom, B., Ward, W. and Pradhan, S. (2000). The CU Communicator: An Architecture for Dialogue Systems, ICSLP, Beijing.

6.4.3 Additional Alternative Input Devices

Control devices that require a manual input impose restrictions on the operator's posture at the control station. Moreover, often they require the operator's gaze be directed at the control device and keep the operator's hands busy. There are numerous alternative controls that have the potential of providing novel means of interacting with UMV systems (e.g., hands-free, head-up input). Speech recognition technology, described in detail above, is one such technology. Non-conventional controllers that do not require a direct mechanical linkage between the operator and the input device are desirable for supplementing manual control. These alternative controls use signals from the brain, muscles, voice, lips, head position, eye position, and gestures. Some of these alternative controls are not yet commercially available or configured to facilitate integration with software under development for supervisory ground control station applications. Plus, the control achieved with many hands-free devices can be described as rudimentary. Any UMV application must take into account the respective dimensionality, accuracy, speed and bandwidth of control afforded by each alternative input device. Of these alternative input devices, speech recognition is the only technology with sufficient maturity and reasonable cost to be considered a near-term candidate for UMV control station application (TRL Rating #7). Since speech recognition technology was described earlier, this section includes brief overviews of the other alternative input devices whose Technology Readiness Levels range from 1 (EEG-based control) to 4 (gesture and eye-based control).

6.4.3.1 Gesture-Based Control

Hand and body gestures are an important component of communication. Gesture-based control seeks to exploit this channel for system control. The head, hands and body can be localized in space using trackers, video techniques, gloves or suits. Trackers (mechanical, electromagnetic, ultrasonic, and optical) are devices that allow one to measure the position and orientation of a body part in space [1]. Video techniques use image processing in order to identify a specific body part and then reconstruct its position, orientation and posture from two-dimensional video images [2]. Gloves and suits allow one to measure the relative positions and angles of body components. A directory of manufacturers of gesture capture devices is available [3]. Perhaps the most highly developed for system interactions are devices that employ glove-based electronic input. For applications in which the body and hands are involved in other activities, gesture-based control for hands-free operation may best involve detecting defined movements or positions of the operator's face or lips. For instance, optical and ultrasonic sensing technologies have been used to monitor an operator's mouth movement [4]. Two candidate control approaches include processing lip movements to provide 'lip reading' and translating symbolic lip gestures into control inputs [5].

One challenge with gesture-based control is identifying the beginning and end points of a gesture [1]. Typical solutions require the operator to take a 'default' posture between gestures, which serves as an anchor for the system. Another problem is detecting whether a gesture is addressed to the recognition system or is a part of normal interpersonal communication. Creating an active zone in which gestures are effective is one solution. Given that a specific gesture can be reliably discriminated from other activity, there are three styles of input that can be made with gestures [1]. With "direct input", the features of the gesture generate kinematically similar actions in the task domain (e.g., one-to-one control of a robot hand). With "mapped input", features of the gesture are mapped in some logical fashion to actions in the task domain (e.g., number of raised fingers indicating a parameter level). For "symbolic inputs", features of the gesture are interpreted as commands to the system. Most uses of facial expressions would fall into the latter category.

A potential UMV control application is illustrated by a study that examined continuous cursor controllers to designate targets in a stereoscopic three-dimensional tactical map resident in a manned aircraft station simulator [6]. The tracking volume was remote from the actual map so that hand movements were actually

made in a space close to the aircraft controls rather than within the volume of the map. This hand volume was reduced in scale so that hand movements were small compared with the size of the map. Results showed that target designation was faster with an ultrasonic hand tracker compared to designation with a four-axis joystick and a voice control system.

6.4.3.2 Gaze-Based Control

Operators naturally look at objects that they want to manipulate or use. For applications in which the operator views a display during control operations, harnessing the direction of gaze promises to be a very natural and efficient control interface. With such control, the computer initiates a predefined action once it receives an input based on the operator's point-of-gaze [7]. For example, gaze-based control could be used to designate points of interest on a display showing the view from a UMV-mounted camera. In addition to command-and-control applications, eye gaze can be used to detect visual attention and adapt the application based on this information [8]. For UMV applications, an intelligent decision aiding system might adapt the display format or tailor active speech commands based on the operator's point of gaze.

Unless the head is stationary (or, with some systems, held within a small motion box), determining eye gaze point also involves tracking the head position/rotation. Predominant eye tracking techniques can be classified as electro-oculographic, scleral coil, and optical methods. The optical classification is the largest of these categories and several methods within this category are the most commonly used for gaze-based control (e.g., corneal reflection trackers) [9]. The most frequent problem with gaze-based control is avoiding what Jacob [10] dubbed the "Midas touch" problem, with commands activating where ever the operator gazes. Careful interface design is also necessary to ensure that the operator's head and/or eye movements during task completion are natural and not fatiguing. Rather, natural head and eye movements should be used to provide a direct pointing capability that can be combined with other control modalities to command activation. Plus, the control design needs to take into account the accuracy limits of the gaze measurement system and its operation under variable illumination environments [9].

6.4.3.3 Electromyographic (EMG)-Based Control

EMG-based control uses the electrical signals that accompany muscle contractions, rather than the movement produced by these contractions, for control. Electrodes positioned on the surface of the skin detect these electrical signals (e.g., produced during an operator's clenching of the jaw). Next, the signal's parameters are translated into a control input with processing. The simplest algorithm employs an on-off control based on the level or rate of change of EMG activity. For example, if muscle activity at one electrode site exceeds some threshold, a prosthetic hand opens. Above-threshold activity at another site causes the hand to close. Control can also be based on EMG patterns rather than on levels or rates of change [11].

EMG-base control is also a potential input device for computer systems. Research has shown that signals extracted from electrodes on the forehead can be used to control the movement of a cursor to track computer-generated targets, as well as provide a quick, accurate discrete on/off response [12]. Thus, for UMV applications, signals from electrodes positioned on the operator's face may provide an alternative hands-free, head-up binary input response. Continued development in EMG-based control is required to optimize the signals employed, assess the stability of the electrode contact over time, and minimize the effect of operator movement and external electrical activity on signal recordings [11].

6.4.3.4 Electroencephalographic (EEG)-Based Control

Electrodes positioned on the surface of the scalp can record signals that represent a summation of the electrical activity of the brain. Although much of the recorded EEG appears to be noise-like, it does contain specific rhythms and patterns that represent the synchronized activity of large groups of neurons. There are two general approaches for translating the electrical activity of the brain into a control signal. In one approach, EEG patterns are brought under conscious voluntary control with training and biofeedback. For example, voluntarily increasing the EEG activity in a specific frequency band above a threshold might be used to turn a switch on. Another approach harnesses involuntary, naturally occurring brain rhythms, patterns, and responses that correspond to human sensory processing, cognitive activity or motor control. For example, an operator might imagine moving their right hand to push a button. The computer would recognize the EEG pattern associated with this movement preparation and operate the right-hand button without further operator action. Although detection of these signals is easily accomplished with inexpensive components, optimization of this alternative control requires minimizing the time required for signal processing and developing easily donned electrodes [11,13,14].

EEG-based control has been demonstrated for several applications: cursor control, alphanumeric input, binary operation of a neuromuscular stimulator, and roll-axis control of a motion simulator [14,15]. To date, only rudimentary control has been achieved. However, the ability to make a system input, albeit crude, without lifting a finger, uttering a sound, or directing one's gaze, inspires the dream of someday enabling a genuine "thought-based interface".

6.4.3.5 Multi-Modal Input Design

For both manual and alternative controls, in addition to considering the general adequacy of the candidate control, the specific mapping of the input device to control tasks must be addressed. It is unlikely that a single input device will be adequate for all the control functions required in a particular application. A specific input device will be elegantly appropriate for some control tasks and clearly inappropriate for others. For example, speech-based control can be useful for a variety of control tasks, but use of a speech command to designate a position on a two-dimensional surface can be cumbersome. In contrast, gaze-based control is efficient for designating a position on a map display, but an auxiliary control modality is more useful for commanding the system to act on the designated location. This action command might be a voice utterance [16] or voluntary facial muscle activation [17]. The use of multiple control input devices capitalizes on using voluntary gaze direction to rapidly designate a position and a voice utterance or voluntary facial muscle activation (EMG) commands to quickly initiate an action. A multi-modal input method that combines speech and touch screen operation was also found to create a more operator-friendly interface [18]. Thus, task-controller mapping must take into account how best to increase overall functionality by using multiple input devices.

6.4.3.6 References for Additional Alternative Input Devices

- [1] McMillan, G.R. and Calhoun, G.L. (2000). Gesture-based Control, International Encyclopedia of Ergonomics and Human Factors, New York: Taylor and Francis, Inc., Volume 1:237-239.
- [2] Borghi, F., Lombardi, L. and Porta, M. (2005). Basic hand gesture recognition for human-computer communication. Proceedings of the 11th International Conference on Human-computer Interaction, CD-ROM.
- [3] Buxton, B. (2005). A directory of sources for input technologies. Available at <http://www.billbuxton.com/InputSources.html>

- [4] Hashimoto, M., Yonezawa, Y. and Itoh, K. (2005). An alternative GUI interface using air propagated ultrasonic waves and sound in mouth. Proceedings of the 11th International Conference on Human-computer Interaction, CD-ROM.
- [5] McMillan, G.R., Eggleston, R.G. and Anderson, T.R. (1997). Nonconventional controls. In: Salvendy (Ed), Handbook of Human Factors and Ergonomics, 2nd edition, New York: John Wiley and Sons, pp. 729-771.
- [6] Liggett, K.K., Reising, J.M., Beam, D.J. and Hartsock, D.C. (1993). The use of aiding techniques and continuous cursor controllers to designate targets in 3-D space. Proceedings of the Human Factors Society, 11-15.
- [7] Fono, D. and Vertegaal, R. (2005). EyeWindows: evaluation of eye-controlled zooming windows for focus selection. Proceedings of Human Factors in Computing System (CHI) '05). New York: ACM Press.
- [8] Hyrskykari, A., Majaranta, P. and R  ih  , K.-J. (2005). From gaze control to attentive interfaces. Proceedings of the 11th International Conference on Human-computer Interaction, CD-ROM.
- [9] Leger, A. and McMillan, G. [Chairs]. (1998). Eye-based control. In: Alternative Control Technologies, RTO-TR-7, 44-59.
- [10] Jacob, R.J.K. (1991). The use of eye movements in human-computer interaction techniques: what you look at is what you get. ACM Transactions on Information Systems (TOIS), 9, 152-169.
- [11] Leger, A. and McMillan, G. [Chairs]. (1998). Biopotential-based Control. In: Alternative Control Technologies, RTO-TR-7, 44-59.
- [12] Nelson, W.T., Hettinger, L.J., Cunningham, J.A., Roe, M.M., Lu, L.G., Haas, M.W., Dennis, L.B., Pick, H.L., Junker, A. and Berg, C.B. (1996). Brain-body actuated control: Assessment of an alternative control technology for virtual environments. Proceedings of the 1996 Image Conference, 225-232.
- [13] Wolpaw, R.J., Birbaumer, N., McFarland, D.J., Pfurtscheller, G. and Vaughan, T.M. (2002). Brain-computer interfaces for communication and control. Clinical Neurophysiology, 113, 767-791.
- [14] Vaughan, T.M., Heetderks, W.J., Trejo, L.J., Rymer, W.Z., Weinrich, M., Moore, M.M., K  bler, A., Dobkin, B.H., Birbaumer, N., Donchin, E., Wolpaw, E.W. and Wolpaw, J.R. (2003). Brain-computer interface technology: A Review of the Second International Meeting. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11, 94-109.
- [15] Nasman, V.T., Calhoun, G.L. and McMillan, G.R. (1997). Brain-actuated control and head mounted displays. In: J. Melzer and K. Moffitt (Eds.), Head mounted displays: designing for the user. New York: McGraw-Hill, 285-312.
- [16] Hatfield, F., Jenkins, E.A., Jennings, M.W. and Calhoun, G.L. (1996). Principles and guidelines for the design of eye/voice interaction dialogs. HICS Third Annual Symposium on Human Interaction with Complex Systems, 10-19.

- [17] Surakka, V., Illi, M. and Isokoski, P. (2004). Gazing and frowning as a new technique for human-computer interaction. *ACM Transactions on Applied Perception*, 1, 40-56.
- [18] Nakagawa, S., Zhang, J.X. and Chengcharoen, W. (1995). Multi-modal interface with speech and touch screen. *Proceedings of the Sixth International Conference on Human-Computer Interaction*, 213-218.

6.5 DATA DISPLAY TECHNOLOGIES

6.5.1 Head-Mounted Displays

6.5.1.1 Description of Technology

A head-mounted display (HMD) presents real video imagery or synthetically generated visual imagery via a head-mounted optic system with very small displays attached to a helmet, visor, or set of spectacles (see Figure 6-3). There is a wide range of technologies and approaches associated with today's HMD systems, including the type and quality of image display, monocular versus bi-ocular design, the ability to display colour images, the ability to effectively display stereoscopic three dimensional (3D) images, system size/weight, and the ability to concurrently view the local external environment. As this section is intended primarily as a short summary of the HMD technology and its relevance to UMVs, interested readers should refer to [1,2,3] for more comprehensive coverage of this area.



Figure 6-3: Examples of HMDs.

HMDs can support either immersive or augmented reality applications, depending upon the transparency of the head-mounted optics. Immersive HMDs require the user to view only the image presented via the HMD optic system, while augmented reality HMDs allow the user to “see-through” the HMD display, thus combining imagery from the HMD with the surrounding real-world visual field. This section only considers immersive HMD display technology, i.e., designs that occlude the subject's view of his/her immediately surrounding physical environment. Augmented reality technology is discussed in Section 6.5.2.

This section also only considers head-coupled HMD applications (i.e., the HMD visual image is updated in response to head movements, via a position tracking sensor that provides the computer with the current head location/orientation information). Head-coupled HMDs enable a synthetically generated visual scene to be continually modified in response to head movements so that, no matter how the user moves, objects in the viewed scene appear to remain in stable locations (thus providing the impression that the user is moving within the virtually generated space). Alternatively, in tele-operated robotic systems, the motion of the user's head can be used to control the position/orientation of a remote camera (or other robotic action) [4]. Head-coupled HMDs offer the highest potential degree of immersiveness and utility. However there remain many limitations due to existing technology, as will be discussed below.

Depending upon the particular UMV application, it may be critical for a HMD to convey accurate depth information in an intuitive and accurate manner. Although all HMDs can convey a sense of depth and distance using conventional two-dimensional depth cues (including linear perspective, interposition, relative size, texture gradients, etc.), certain HMDs also have the potential to portray depth via various stereoscopic techniques. Stereopsis can provide an intuitive, unambiguous cue for depth and it dominates most other depth cues. Dichoptic presentation involves using two monitors to portray a scene, one monitor per eye, each with its appropriate viewpoint for that eye's position in space [5]. This method utilizes binocular fusion to yield stereopsis. Electronic shutter glasses use one monitor to present a stereoscopic image by providing two alternating views of a scene (corresponding to the viewpoint disparity between the two eyes), synchronized to the frame rate, such that one interleaved frame in each pair is presented to each eye. Section 6.5.3 contains more information on various 3D display technologies.

6.5.1.2 Actual or Potential Application to UMs

HMDs have been found to enhance wide-area search and intercept operations performed by manned aircraft [6]. A potential advantage of head-coupled control versus manual control over one's viewpoint is the addition of ecologically relevant proprioceptive cues which provide motion information based on vestibular inputs, joint angles, muscle lengths, and tendon tension during head movements. Head-coupled HMDs are also hypothesized to reduce cognitive processing demands in achieving new viewpoints. Some studies have suggested that head-coupled configurations facilitate awareness of areas already searched, thereby potentially reducing the re-scanning of those same areas [7]. Thus, HMD technology may benefit UMV operators, especially since reduced situation awareness is often a by-product of current UMV control station designs [8,9]. It is theorized that a HMD could enhance the operator's large-area searches and overall spatial orientation of the remote environment, while larger, high-resolution fixed console displays could be reserved for any target fine discrimination tasks. Other expected advantages of HMDs include hands-free control and intuitive operation. However, studies investigating the benefits of HMDs have so far produced mixed results. Below is a summary of the recent research in the area, categorized by type of UMV: UAV, UGV and UUV.

6.5.1.2.1 UAVs

HMDs have been demonstrated to have a positive impact of certain UAV control tasks. A study [10] explored UAV operator control of a remotely-operated helicopter using an omni-directional camera controlled by a head-coupled HMD. The HMD system was found to promote operator immersion, encouraging a feeling of 'presence' as though the operator was physically in the vehicle. The HMD also resulted in faster and more accurate completion times in a simulated helicopter control task, compared to the alternative of attempting to control the helicopter while viewing it directly from the ground. These results support claims that HMDs can provide increased situation awareness. However, the non-HMD condition was somewhat lacking in that it did not include a fixed-display out-the-window view from the helicopter, so it is unclear whether viewpoint location or head-coupled HMD provided the observed improvements. Another study [11] explored HMDs for small UAV applications. The task involved piloting a small UAV past a ground target and then turning around at various distances to re-acquire that same ground target. The researchers found that the use of a head-coupled HMD resulted in faster and more successful re-acquisition of the ground target than when using a conventional display of imagery from the UAV's nose-camera. However the horizontal field-of view was nearly twice as large for the HMD as compared to the conventional display, which may have contributed to these findings. Additionally, all subjects complained of discomfort when wearing the HMD. Nonetheless, there is research support for the proposition that HMDs can provide greater situation awareness resulting in increased UAV operator performance.

An early experiment at the TNO Research Institute was conducted to explore the applicability of a head-slaved camera system in UMV applications [12]. To overcome some possible drawbacks of HMDs (e.g., weight), a HMD was compared with a head-slaved dome projection (Figure 6-4). To overcome the possible drawbacks of transmission delay, a method was introduced to compensate for the spatial distortions. This technique, called delay handling, preserves the correct spatial relation between the viewing direction of the camera and the operator, by presenting incoming images in the camera viewing direction at the moment the images were recorded, and not in the actual viewing direction of the operator. The results showed that delay handling is successful in supporting the perception of correct spatial relations. No differences in task performance were found between the actual HMD and the dome projection.

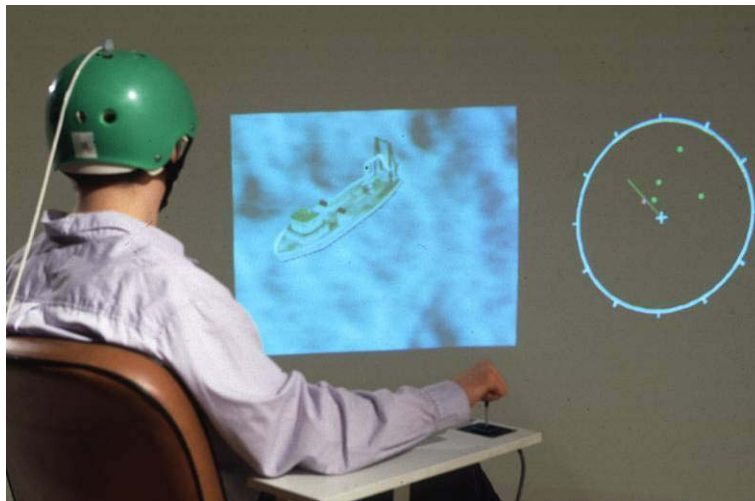


Figure 6-4: Dome Projection in which the Camera Direction is Head-Coupled, and the Operator Receives High Quality Proprioceptive Feedback on Camera Viewing Direction.

In follow-on studies at TNO, researchers compared operator performance with head-coupled camera control, and HMDs with manual camera control [13,14]. Subjects had to locate targets as fast as possible. The results showed that head-slaved camera control increased search speed, but enlarged the search path as compared to manual (joystick) control. An increased susceptibility, during head-slaved control, to mismatches between visual information and proprioceptive information may account for these findings. Additional measures of head movements showed that eye-head coordination was altered during head-slaved camera control. Since in these experiments, proprioceptive feedback was available in the manual control condition as well (the images were presented on a projection screen under the correct camera viewing direction), the findings imply an additional advantage of head-slaved control compared with manual control without proprioceptive feedback (as would be the case when using a fixed monitor). However, [15] found that employing simulated HMD images projected onto a large screen resulted in higher UAV operator performance than when they used an actual HMD, and [16] found that use of a conventional joystick for UAV control resulted in better performance than the head-coupled HMD. These latter results converge with several other studies, as detailed below.

Two experiments were conducted at the U.S. Air Force Research Laboratory to evaluate the usefulness of HMDs for UAV tasks involving the search for ground targets (Figure 6-5) [17,18]. The overall approach was to compare the utility of a manual joystick with associated stationary display monitor (the Baseline Condition) to that of various head-coupled HMD configurations. Specifically, gimbal camera orientation (azimuth and

ADVANCED UMV OPERATOR INTERFACES

elevation angle) was controlled via either a right-hand control stick or head-coupled HMD, while camera zoom was always controlled with the left-hand forward/aft stick. In one study [17], the task involved conducting a wide area search followed by a target identification task. The wide-area search was conducted by using the baseline configuration (control stick and stationary display monitor) or a head-coupled HMD. The target identification task was always conducted using the higher resolution stationary display monitor, as the HMD did not have the required resolution to afford fine discrimination. Thus, in the HMD conditions, there was a need to switch displays between search and identification tasks. The results failed to show any benefit for HMD-based configurations. Search time was shorter and workload was lower with the Baseline Condition than any of the HMD conditions. Additionally, many subjects experienced discomfort and simulator sickness symptoms with the HMD configuration.



Figure 6-5: UAV Workstation with Head-Coupled HMD and Stationary CRT Camera Displays.

A follow-on study [18] was conducted to specifically evaluate the utility of a head-coupled HMD for the SO's conduct of a 360-degree large area search for multiple ground targets. This study did not include the additional target identification step that had required a switch from HMD to a stationary display in the previous study. Six camera control/display configurations were evaluated; two involved the stationary display monitor (each with a different rate gain joystick) and four involved a HMD. The four HMD configurations varied in the degree to which the camera moved with head movements. One "hybrid" configuration was also evaluated whereby the gimballed camera orientation could be controlled with both the head and the joystick simultaneously. Results indicated fewer unique targets were prosecuted with the HMD than with the fixed display monitor. Head-coupled control also resulted in more duplicate target designations, higher workload, and lower situation awareness ratings. These results suggest that there is no clear advantage for head-coupled HMDs in the performance of large-area search tasks. In fact, performance significantly decreased in some experimental manipulations involving the HMD.

A similar set of studies were conducted utilizing a simulation of a smaller UAV [19,20]. One study compared a conventional display monitor to a HMD for target search, discrimination and designation tasks [19]. Although there were no differences between display conditions for target detection accuracy, the conventional display condition enabled more targets to be correctly identified from further away and allowed for more

accurate cursor designation of those targets. Additionally, subjects experienced far more discomfort (e.g., nausea, disorientation, eyestrain) with the HMD condition. In a follow-on study [20], these researchers explored the effect of including various auditory cues (mono, stereo, 3D spatialized) to the ground target location with the comparison of visual display conditions (conventional, head-coupled HMD). The results confirmed earlier findings that conventional displays resulted in significantly more precise target designations and fewer reports of discomfort. However, although HMD conditions yielded higher operator workload ratings than conventional displays across all conditions, 3D spatialized cueing reduced HMD workload levels significantly.

6.5.1.2.2 UGVs

HMDs have characteristics that potentially offer many advantages over conventional UGV operator control units [21]. Advantages identified included the system's light weight, decreased power consumption, daylight readability, and theorized improvements in operator situation awareness and telepresence. HMDs have also been demonstrated in UGV systems [22]. HMDs were found to be beneficial during a demonstration of the feasibility of utilizing a dune buggy as a UGV travelling complex terrain [23]. Other researchers conducted a study which found telepresence, created from use of stereo TV imagery displayed in an HMD, permitted operators' to drive UGVs at higher speeds and on steeper side slopes by providing an enhanced sense of spatial/geographic awareness [24]. There has also been implementation of HMDs into operational UGV systems. Man-portable UGVs are completing missions in current military operations with operators who wear monocular HMDs [25]. Soldiers are successfully controlling the UGVs with a portable joystick and HMD to explore cave complexes and suspected enemy compounds. Packbots' success in combat environments demonstrate HMDs' increasing and promising role in UGV control station design.

6.5.1.2.3 UUVs

Although few formal studies have been conducted in this area, the potential value of HMDs to UUV systems seems promising for underwater operations and operator training [26,27,37]. Other researchers have described the potential importance of providing UUV operators with meaningful cues for situation awareness, good workspace visibility, and vehicle behaviour feedback for effective performance [28]. The testbed they designed to address underwater telerobotics included a head-coupled HMD option. Though there is little research specifically addressing HMDs' effectiveness compared to other systems in UUV operation, the difficulties for operators controlling UAVs and UGVs are similar to those in underwater vehicles and so it is reasonable to assume that research on HMDs in these systems could transfer to UUVs.

6.5.1.3 Technology Maturity, Challenges, and Unresolved Issues

HMDs have improved considerably since they were first introduced into the commercial market. However, there is still much research needed before they achieve widespread appeal in military and consumer applications. Research areas discussed below include ergonomic issues, resolution, time latencies, field-of-view, and the occurrence of motion-sickness type symptoms.

6.5.1.3.1 Ergonomic Issues

Ergonomic issues associated with HMDs can be primarily attributed to anthropometric, biomechanic, and psychomotor concerns. Most HMDs involve some encumbrance by the user, though this varies with particular equipment chosen. Lack of fit is a primary complaint of users [29]. This includes inappropriate fit, movement limitations, excessive weight and/or size, and improper distribution of the weight. HMD weight

also has the potential to alter eye-head coordination. Suggestions exist for improving fit [29]. Newer displays are being developed to minimize size and weight such that they can be clipped onto existing eye-pieces, although other tradeoffs exist (limited resolution, small field-of-view, display placement within larger visual field, etc.). Furthermore, certain HMDs enable the display system to be removed or rotated out of the way to afford intermittent HMD use within a larger real-world work task. However it is unknown which method is most preferable for various UMV applications. Additional information regarding ergonomic issues can be found elsewhere [1,3,4]. Much research is needed to improve the many ergonomic issues of HMDs.

6.5.1.3.2 Spatial Resolution

Spatial resolution is a measure of the level of detail available in a visual display [2]. However, it can be a misrepresented parameter in HMD specifications. Often, resolution is described in terms of number of pixels in a display. However, the size of the display and its distance from the observer also contribute to the effective resolution. Increasing display field-of-view reduces effective resolution by enlarging each pixel in the same manner. Therefore a more effective manner in which to specify resolution is in terms of visual angle subtended per pixel, termed 'angular resolution'. Angular resolution is poor in most current HMDs, far lower than the resolving capability of the human eye (approximately 1 arc min visual angle or less [2]). Thus researchers have found resolution to be a limiting factor in HMD utilization [30]. An additional confusion with assessing spatial resolution of color HMDs is associated with the pixel-type used for determining angular resolution. Color display pixels are often formed by grouping 3 or 4 monocular pixels of different wavelengths (such as red, green, blue). Display manufacturers sometimes report the number of pixels and angular resolution based upon the total number of monocular pixels available instead of available color pixels.

Research is needed to better define spatial resolution requirements of HMDs for the range of envisioned UMV tasks. Additionally, research is needed to improve spatial resolution. One promising technology in this area is the virtual retinal display [31].

6.5.1.3.3 Time Latencies

Time delays exist between movements made by the user's head (which are tracked by a position-sensing device) and the response of the HMD scene to those movements, due to delays in position tracking and image generation [4]. Time delays between head movements and virtual image response result in loss of visual stability which can affect task performance and generate a sensory rearrangement between visual and vestibular cues of motion. These sensory rearrangements are believed to induce simulator sickness symptoms [32,33,34]. When the additional time delay associated with UMV datalink communications are factored in, the total delay can be on the order of several seconds. Additionally, time delays can affect user acceptance [7].

Specifications are needed for acceptable HMD time delay for various UMV applications, factoring in the delays associated with communication with the vehicle. Acceptable time delays for UAV operations may not be acceptable for fast-moving UAV systems. Research is also needed on methods to minimize the negative effects of time delay, such as through the use of prediction techniques for head motion.

6.5.1.3.4 Display Field-of-View (DFOV)

DFOV is the visual angle subtended by the display screen from a given observer location [35]. This parameter, described in terms of its horizontal and vertical components, is often desired to be large to promote a sense of immersiveness (i.e., presence) and to improve task performance through the utilization of

peripheral vision (limited DFOV displays result in the development of altered scanning strategies). However, a trade off that occurs when one tries to increase DFOV using an existing display is a corresponding reduction of screen resolution. Given a fixed display size, the only way to increase DFOV is to either magnify the display using optics or move the eye closer to the screen. In either case, pixel size increases in the same proportion as screen size (since both are fixed values). As pixel sizes increase, display resolution decreases. Research is needed to better understand DFOV requirements for various UMV applications. Additionally, the relation between DFOV and geometric field-of-view (zoomed in or zoomed out images) and its effect on UMV operator performance and comfort is needed [35].

6.5.1.3.5 Simulator Sickness/Cyber Sickness

Simulator sickness (also termed cyber sickness) is a form of motion sickness that occurs as a result of experiencing computer-simulated visual environments [35]. Symptoms include nausea, fatigue, headache, eye-strain, dizziness, malaise, and blurred vision. Besides the deleterious effects associated with simulator sickness, experiencing these symptoms may result in reduced desire to interact with the provoking system in the future, thus potentially hampering overall mission effectiveness. HMD usage has been strongly linked with increased levels of simulator sickness in many studies including those involving UMVs [17,19,20]. Although some guidelines exist, more research is needed to fully characterize and alleviate simulator sickness in UMV-related HMD applications.

6.5.1.3.6 Other Issues

Other research issues include the need to better understand and mitigate workload associated with HMD usage. Due to ergonomic concerns as well as the need to constantly move one's head to change one's viewpoint, workload and fatigue are real concerns associated with this technology [19] and mitigation techniques must be explored [18]. Head tracking technology and research is also needed to define minimum accuracy requirements for various UMV systems and to enable unencumbered operations [36]. Display brightness and contrast are also issues, especially for applications in outdoor environments.

6.5.1.4 References for Head-Mounted Displays

- [1] Kalawsky, R.S. (1993). *The Science of Virtual Reality and Virtual Environments*, Reading, MA: Addison-Wesley.
- [2] Kocian, D.F. and Task, H.L. (1995). Visually coupled systems hardware and the human interface. In: W. Barfield and T.A. Furness (Eds.), *Virtual Environments and Advanced Interface Design*, New York: Oxford University Press.
- [3] Melzer, J.E. and Moffitt, K.W. (1997). *Head-mounted Displays: Designing for the User*. New York: McGraw-Hill.
- [4] Durlach, N.I. and Mavor, A.S. (Eds.). (1995). *Virtual Reality: Scientific and Technological Challenges*, Washington, DC: National Academy Press.
- [5] May, J.G. and Badcock, D.R. (2002). Vision and Virtual Environments. In: K.M. Stanney (Ed.) *Handbook of Virtual Environments*, Mahwah, NJ: Lawrence Erlbaum Associates.
- [6] Geiselman, E.E. and Osgood, R.K. (1994). Utility of Off-Boresight Helmet Mounted Symbolology During a High Angle Airborne Target Acquisition Task. *Proceedings of the SPIE Conference Helmet & Head-Mounted Displays & Symbolology Design Requirements*, Vol. 2218, 328-338.

- [7] Pausch, R., Proffitt, D. and Williams, G. (1997, August). Quantifying Immersion in Virtual Reality. Proceedings of SIGGRAPH 97, Computer Graphics Proceedings, Annual Conference Series, ACM SIGGRAPH, Los Angeles, CA, 13-18.
- [8] Gawron, V.J. (1998). Human factors issues in the development, evaluation, and operation of uninhabited aerial vehicles. AUVSI '98: Proceedings of the Association for Unmanned Vehicle Systems International, Huntsville, AL, 431-438.
- [9] Gawron, V.J. and Draper, M.H. (2001). Human dimension of operating manned and unmanned air vehicles, NATO RTO Workshop on Architectures for the Integration of Manned and Unmanned Air Vehicles (SCI-100), Fairfax, VA.
- [10] Koeda, M., Matsumoto, Y. and Ogasawara, T. (2002). Development of an immersive teleoperating system for unmanned helicopter. Proceedings. 11th IEEE International Workshop on Robot and Human Interactive Communication, 25-27 September, 47-52.
- [11] Naylor, M., Reid, L. and Delaurier, J. (2004). Investigation of the effect of head-slaved camera motion on image tracking in uninhabited air vehicles, Canadian Aeronautics and Space Journal; September, Vol. 50, 199-205.
- [12] van Erp, J.B.F. and Kappé, B. (1996). Computer Generated Environment for steering a simulated unmanned aerial vehicle. TNO report TM-96-A039. Soesterberg, The Netherlands: TNO Human Factors Research Institute.
- [13] van Erp, J.B.F. and van den Dobbelsteen, J.J. (1998a). Head-slaved and manual remote camera control with time delays. TNO report TM-1998-A076. Soesterberg, The Netherlands: TNO Human Factors Research Institute.
- [14] van Erp, J.B.F. and van den Dobbelsteen, J.J. (1998b). Head slaved camera control, time delays, and situational awareness in UAV operation. Report TM-1998-A075. Soesterberg, The Netherlands: TNO Human Factors Research Institute.
- [15] de Vries, S.C. and Padmos, P. (1997). Steering a simulated unmanned aerial vehicle using a head-slaved camera and HMD, Proceedings of the SPIE – The International Society for Optical Engineering; Vol. 3058, 24-33.
- [16] de Vries, S.C. (2001). Head-slaved control versus joystick control of a remote camera, TNO-report TM-01-B008, Soesterberg, The Netherlands: TNO Human Factors Research Institute.
- [17] Draper, M.H., Ruff, H.A. and LaFleur, T.C. (2001). The effects of camera control configuration on teleoperated target search tasks. Proceeding of the Human Factors and Ergonomics Society 45th Annual Meeting, 1872-1877.
- [18] Draper, M.H., Ruff, H.A., Fontejon, J.V. and Napier, S. (2002). The effects of head-coupled control and head-mounted displays (HMDs) on large-area search tasks. Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting, 2139-2143.
- [19] Morphew, M.E., Shively, J.R. and Casey, D. (2004). Helmet-mounted displays for unmanned aerial vehicle control; Proceedings of SPIE – The International Society for Optical Engineering, Vol. 5442, 93-103.

- [20] Dowell, S.R. and Shively, R.J. (2005). Synergy of virtual visual and auditory displays for UAV ground control stations. Proceedings of International Symposium on Aviation Psychology, Oklahoma City, 155-161.
- [21] Browne, M. and Moffitt, K. (1996). A head-mounted display system for UGV control stations. AUVSI '96; Proceedings of the 23rd Annual Association for Unmanned Vehicle Systems International Symposium and Exhibition, Orlando, 15-19 July, 705-715.
- [22] Kron, A. and Schmidt, G. (2005). Haptic telepresent control technology applied to disposal of explosive ordnances: principles and experimental results. Proceedings of IEEE ISIE 2005: International Symposium of Industrial Electronics, June 20-23, Dubrovnik, Croatia.
- [23] McDonnell, J.R., Solorzano, M.R., Martin, S.W. and Umeda, A.Y. (1990). A head coupled sensor platform for teleoperated ground vehicles, Unmanned Systems, Fall, Vol. 8; 33-38.
- [24] Metz, C.D., Everett, H.R. and Myers, S. (1992). Recent developments in tactical unmanned ground vehicles. Proceedings of The Association of Unmanned Systems International, Huntsville AL, 22-24 June.
- [25] Hromadka, T.V. and Melzer, J.E. (2003). Results of using helmet-mounted displays to control robots in Afghanistan. Proceedings of SPIE – Helmet- and Head-Mounted Displays VIII: Technologies and Applications, Clarence E. Rash, Colin E. Reese, Editors, Vol. 5079, 222-231.
- [26] Pioch, N.J., Roberts, B. and Zeltzer, D. (1997). A virtual environment for learning to pilot remotely operated vehicles. Proceedings of The International Conference on Virtual Systems and Multi Media VSMM '97, 10-12 September, 218-226.
- [27] Boulton, T. (2000). DOVE: Dolphin omni-directional video equipment. Proceedings of the IASTED International Conference on Robotics and Automation, August 14-16, Honolulu, Hawaii.
- [28] Murray, S. and Murphy, D. (1996). Underwater telerobotics and virtual reality: A new technology partnership, PACON, Honolulu, HI, 20 June.
- [29] McCauley Bell, P.R. (2002). Ergonomics in Virtual Environments. In: K.M. Stanney (Ed.) Handbook of Virtual Environments, Mahwah, NJ: Lawrence Erlbaum Associates.
- [30] Smith Sr., G.R. and Smith Jr., G.R. (2000). Virtual reality flight trainer for the UAV remote pilot. Proceedings of SPIE – The International Society for Optical Engineering, Vol. 4021, 224-233.
- [31] Bayer, M.M. (2002). Retinal Scanning display: a novel HMD approach for Army aviation, Proceedings of SPIE – The International Society for Optical Engineering, Helmet and Head-mounted Displays VII, Vol. 4711, 202-213.
- [32] Peli, E. (1995). Real vision and virtual reality. Optics and Photonics News, July, 28-34.
- [33] Reason, J.T. and Brand, J.J. (1975). Motion Sickness. London: Academic Press.
- [34] So, R.H. and Griffin, M.J. (1995). Head coupled virtual environment with display lag. In: K. Carr and R. England (Eds.), Simulated and Virtual Realities: Elements of Perception, London: Taylor & Francis.

- [35] Draper, M.H., Virre, E.S., Furness, T.A. and Gawron, V.J. (2001). Effects of image scale and system time delay on simulator sickness within head-coupled virtual environments. *Human Factors*, 43(1), 129-146.
- [36] Martinsen, G.L., Havig, P.R., Post, D.L., Reis, G.A. and Simpson M.A. (2002). Human factor requirements of helmet trackers for HMDs. *Proceedings of SPIE – The International Society for Optical Engineering*, Vol. 5079, 95-103.
- [37] Stoker, B.P.H., Sims, M., Rasmussen, D., Hontalas, P., Fong, T.W., Steele, J., Barch, D., Andersen, D., Miles, E. and Nygren, E. (1994). The Application of Telepresence and Virtual Reality to Subsea Exploration, The 2nd Workshop on Mobile Robots for Subsea Environments, *Proceedings ROV'94*.

6.5.2 Augmented/Mixed Reality Technology

One reason that it is difficult to operate a remote UMV or its sensor is the “limited angular view associated with many remote vision platforms [which] creates a sense of trying to understand the environment through what remote observers often call a ‘soda straw’” [1]. Another reason for the difficulty is the lack of the proprioceptive cues that would normally be available to a driver or pilot situated in a vehicle. One justification for the use of a head-coupled HMD as discussed in the previous section is to give the UMV/sensor operator a proprioceptive sense of the environment: the operator’s proprioceptive sense of the relative pose of his or her head is used as a surrogate for the relative pose of a moving camera, albeit with mixed results.

An alternative approach is to represent multiple sources of sensor data in a mixed reality interface. Conventional interfaces do not integrate multiple sources of information into a coherent representation. For example, Figure 6-6 presents compass direction (upper left), laser range data (second from upper left), video (upper center), sonar data (upper right), map (bottom), and team information (right). All information required for robot control is available in the interface, but it is up to the operator to integrate this information into a meaningful and useful “picture” of what is going on. For operators, this means that the cognitive workload associated with just getting enough awareness to control locomotion can be high enough that it is difficult to interpret imagery, plan strategies, and do other higher-level tasks that are relevant for the mission. This problem is frequently solved by adding more humans to the team who are responsible for mission-level issues [2].

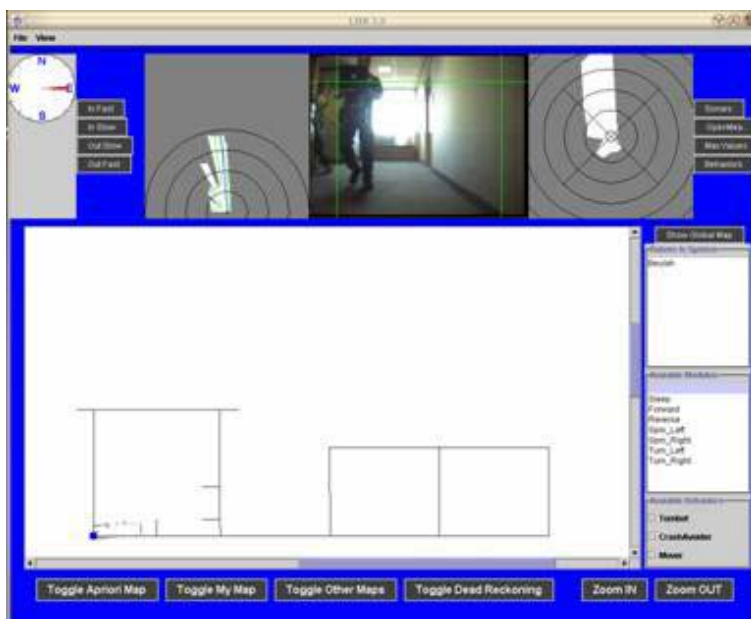


Figure 6-6: A Typical Interface Presents All Sensor Readings Side by Side.

6.5.2.1 Description of Technology

Another approach to this problem is to represent real sensor information in an ecological way [3]. In the robotic domain, one important and useful ecological technique is the use of mixed reality interfaces. Such interfaces combine real data with virtual elements, and range from augmented reality to augmented virtuality interfaces [4]. An example of such interfaces, taken from [5], is shown in Figure 6-7. In this interface, obstacles detected with a range sensor are represented by barrels in a virtual world. This virtual world is augmented with video from the robot. Fusing video, obstacles, and a representation of the robot allow the operator to perceive the relationship between the robot's "shoulders" and the obstacles in the world. This type of mixed reality display uses visualization techniques, such as those developed in gaming, as surrogates for the proprioceptive cues that are missing in remote operation.

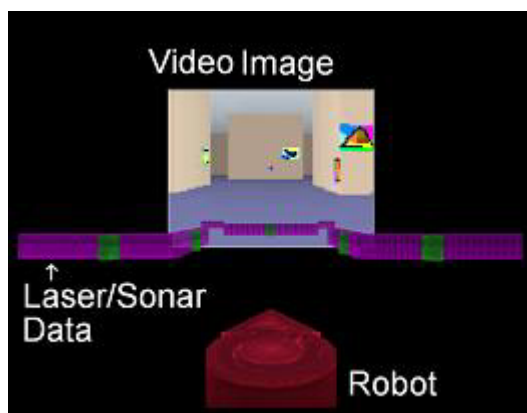


Figure 6-7: Integrated Display of Video, Range Readings, and Robot Representation.

There are a number of different ways for information to be presented in a mixed reality display. This section describes two techniques and shows examples from both UGV and UAV applications. The two techniques that will be shown are the chase perspective and the map-based perspective. Each technique is appropriate for certain types of tasks and modes of interaction between the human and a UMV. The idea that different visualization techniques have uses in different situations is a well-known result in display design, in general, and in augmented reality-based displays, in particular [6].

6.5.2.1.1 *The Chase Perspective*

The chase perspective is illustrated in Figure 6-7. This perspective presents sensor information in a way that supports locomotion, and is a typical representation used in racing games because it allows the direct perception of the relationship between the vehicle and the afforded directions of vehicle movement. Similar to the goal of using a head-coupled HMD to help an operator understand the pose of a movable camera, the chase perspective can be augmented with a visual representation of the pose of the camera relative to the robot. This is illustrated in Figure 6-8. Note, however, that large panning motions may require a shift from the chase perspective as illustrated in Figure 6-9.

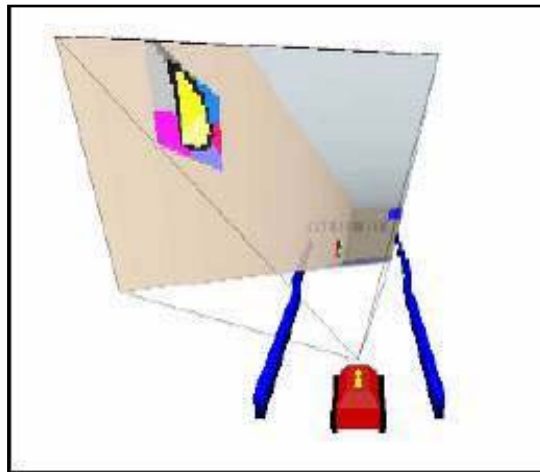


Figure 6-8: Representing the Pose of a Panning Camera.

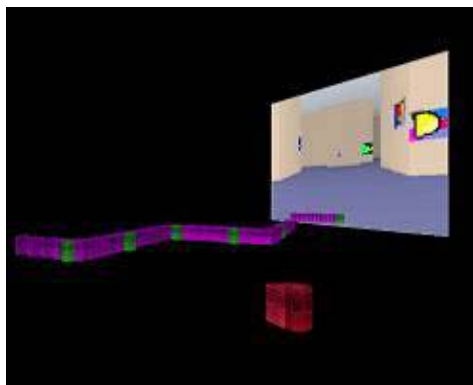


Figure 6-9: Depicting Camera Pose May Require a Perspective Change.

Similar visualization techniques can be used to represent other information such as deviations in terrain, the focal length of a zooming camera [7], and delays in receiving imagery from the robot via quickening [5].

A chase perspective can similarly be used to support aviation with UAVs. An example of the chase perspective is shown in Figure 6-10 [8,9]. In this display, a virtual UAV is included in the display to represent the pose of the UAV relative to the ground. This virtual UAV is overlaid on the video image received from the UAV and allows the operator to directly perceive the attitude of the aircraft with respect to the ground. (In the figure, two virtual UAVs are shown; one indicates the actual pose of the UAV as received from telemetry and the other indicates the commanded pose of the UAV.) The chase perspective shown in Figure 6-10 is taken from an interface that runs on a 5 inch or smaller display.



Figure 6-10: The Chase Perspective for a UAV.

Note that the chase perspective for the UAV is earth-centered rather than pilot-centered. When the operator is on the ground, banking right is not accompanied by a pilot-perceived change in the earth's horizon nor is it accompanied by other vestibular cues. Since the operator is on the ground, the chase perspective adopts a ground-based perspective wherein a bank command is depicted by having the virtual UAV dip its wing in the commanded direction.

It is possible to take this ground-centered perspective a step further. Since a fixed-mount camera rotates when the UAV banks, the operator must switch from a ground perspective to issue commands, to the UAV perspective to interpret video. This switch might be a cause of cognitive workload because the ground-based operator must interpret rotations in the video caused by a banking UAV. An interface that makes both video and bank angle have a ground-centered reference frame is shown in Figure 6-11. This interface is built for a control device called the PhyCon (for Physical Icon) [8]. Rather than using a handheld computer to issue commands to the UAV, a physical model of the UAV is used. When the operator banks the model, the actual UAV also banks. Although it is somewhat difficult to see in the figure, the pose of the aircraft is projected onto the video from a ground-centered reference frame using the chase perspective. This is a type of mixed reality interface [4]. (In practice, there are actually two virtual depictions of the UAV. The first virtual UAV is depicted using the actual telemetry from the UAV. The second virtual is depicted using the commanded pose from the PhyCon. Having both of these projected into the augmented reality display allows the operator to see that the actual UAV is responding appropriately to the commanded pose.)

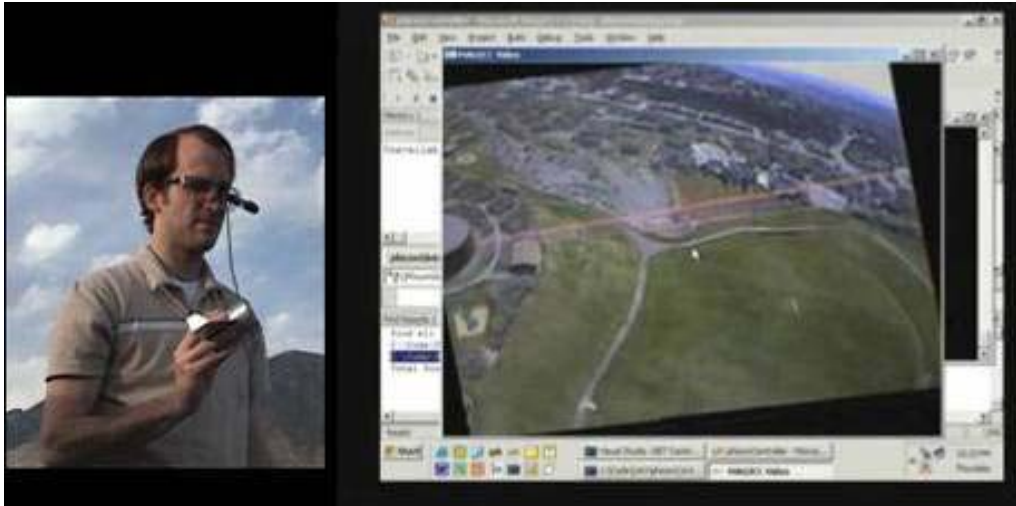


Figure 6-11: Rotating the Video Supports the Ground-Based Perspective of the Remote Operator.

The video feed is digitized and displayed on a computer (in this case, a laptop which presents the video through an eyeglass-mounted display). Prior to presenting the imagery, the telemetry from the UAV is used to rotate the image so that the horizon stays approximately level. This is depicted in Figure 6-11. Rotating the image so that the horizon stays level means that both the video and the UAV attitude are depicted in a ground-relative reference frame.

6.5.2.1.2 *The Map-Based Perspective*

The chase perspective primarily supports locomotion. When it is necessary to operate at the level of navigation or planning, it is often useful to have a map of some sort. For example, many potential UMV missions require some sort of exhaustive or heuristic search. Issuing commands for these searches and depicting the progress of these searches may be easier for the operator if a map-centered reference frame is used [6]. The task is to present map information in a useful way and then to integrate the video into the map using this map-centered perspective.

Figure 6-12 depicts a mixed reality display that integrates a virtual map with video from a robot [10,11]. The virtual map is a 3D rendering of a 2D occupancy grid map created using Konolige's map-building algorithms and software [12]. The video is depicted in this virtual world in such a way that video, map, and robot pose information are simultaneously visible. There are a number of desirable features of such an interface, including

- a) The ability to determine what has been searched and what needs to be searched;
- b) The ability to perceive how the robot is oriented with respect to landmarks in the world; and
- c) The ability to augment map information with icons or other semantic labels.

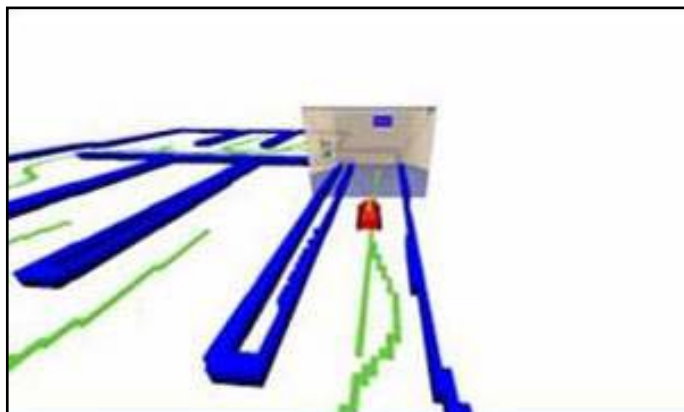


Figure 6-12: An Occupancy Grid Map Can be Used as the Basis for Navigation [10].

These same three elements, video, map, and robot (UAV) pose, can also be used to create a map-centered display for UAVs. In this case, the virtual world can be built on GIS terrain data or satellite imagery, the UAV pose can be depicted on this map with either a north-up or linked orientation [6], and the video from the UAV can be projected into the map with appropriate rotations so that the video is oriented in the same reference frame as the map. Some evidence suggests that using a map-based display helps operators more rapidly “cover” a particular region of interest by supporting better navigation [13]. The techniques described in the next section on various perspectives of the tactical space for 3D visualization can be simplified and applied to the augmented virtuality display. Such an interface is illustrated in Figure 6-13.



Figure 6-13: Augmenting a Terrain Map with Symbology Can Better Support Navigation and Sensor Management [23].

It is important to note that map-based interfaces have been used to construct augmented reality displays in aviation. These displays, which may be either heads-up or head-down and which may be retrofitted to older aircraft [14], are referred to as *synthetic vision* displays [15]. Several human factors studies have been conducted, many showing that there is an increase in navigation-related situation awareness with negligible loss in aviation-related situation awareness [16], presumably because a greater field-of-view and subsequent sense of realism can be obtained with such displays.

6.5.2.2 Actual or Potential Application to UMs

Application of these display technologies to UMs is an area of ongoing work. Research and development of mixed reality displays is being supported via Idaho National Laboratory under the Joint Robotics Program with the intent of developing a fieldable augmented virtuality display for UGVs in the very near future. As part of achieving appropriate levels of technology readiness, human factors studies have been conducted that provide strong evidence that the mixed reality interfaces described herein:

- a) Make it easier to tele-operate a robot [5];
- b) Make it easier to build a map of an area [11,13];
- c) Work well with UGVs that have autonomy that allows interaction beyond tele-operation; and
- d) Make it easier to use a panning camera [10].

The mixed reality displays for UAVs described herein run on small displays that may be appropriate for a dismounted control device of the type considered in the Future Combat Systems program. These interfaces have been demonstrated on laboratory UAVs that are equipped with the same automated controllers used on several class 1 military UAVs.

Research at the Air Force Research Laboratory's Human Effectiveness Directorate is exploring the value of mixed reality display concepts for UAV operation [17,23]. Research to date has focused on improving the situation awareness and performance of a UAV sensor operator for target search tasks through collaboration with Rapid Imaging Software, Inc. (see Figure 6-13). A recent study demonstrated a significant reduction in search time required to find ground landmarks when virtual marking flags were enabled. Future studies will develop guidelines for system update rate, symbology and labelling, declutter techniques and terrain depiction.

Like the occupancy grid-based displays for UGVs, terrain or image-based displays for UAVs are hypothesized to support better navigation, especially when navigation is complex or is performed under adverse visibility conditions [15]. However, an argument made in [18] indicates that the emphasis on realism in these displays may produce designs that are attractive but less effective than they should be. The authors call for designers to avoid "naïve realism" by using caricatures, icons, symbology and other abstracted representations of the kinds of information that an operator desires [19]. Added to this caution is the observation that overuse of symbology can create cluttered displays [20] and that certain types of disruptions can be very difficult to recover from even in the presence of clear symbolic labels [21]. Importantly, if information is sufficient to support precise navigation via augmented reality (synthetic vision) displays, it may also be sufficient to perform autonomous navigation. This may be especially important in areas such as search, where it is desirable to ensure that imagery from the camera efficiently and completely covers a region of the ground [22] and where screen size or team size is small enough that it is challenging for an operator to simultaneously aviate, navigate, and analyze imagery. The complexity of such navigation is illustrated in Figure 6-14.

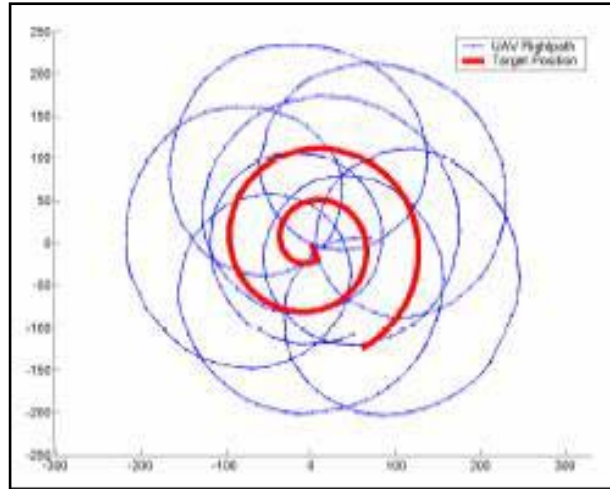


Figure 6-14: UAV Locations (thin blue lines) Required to Support Low Ground Speed, Complete Coverage by a Camera Footprint Spiral (bold red line).

Perhaps the most important potential application of mixed reality displays of the type described herein is in forming a common operating concept for many types of UMVs. The displays rely heavily on visualization techniques used in graphics and gaming, and therefore have some basis in being useful for a large class of operators in a large variety of situations. Moreover, the mixed reality displays described for UAVs are similar in concept to synthetic vision systems.

6.5.2.3 Technology Maturity, Challenges, and Unresolved Issues

The example interfaces described in this section are in the alpha or early beta stages of development. They have all been tested on physical platforms and there have been tests that confirm their usefulness in limited problems. A number of challenges and unresolved issues remain. The most pressing concern is the effects of terrain on visualization and control for both the UAV and UGV platforms. UGVs must frequently operate in outdoor, unstructured environments. While there is mounting evidence that in worlds with a level ground plane, such as inside a building, the UGV mixed reality interfaces work well, it is an open area how to adapt these interfaces to uneven terrain. A similar challenge exists with the UAVs. For class 1 UAVs, the operational altitude is frequently very close to the ground. Since the chase perspective and map perspective can make it difficult to convey information about height above ground to the operator, it may be desirable to use a terrain model and height above ground sensor to autonomously maintain a consistent height above ground.

Another very important challenge is to identify how to transition from one display perspective (e.g., chase view) to another perspective (e.g., map-view) when the operator shifts from one mission phase to another. Questions such as whether the display should automatically adapt to such shifts or whether the operator should explicitly command display changes are important to answer. Fortunately, there is a considerable literature on mode confusion, adaptive displays, automation management policies, and so on.

Other important challenges remain. These challenges include the following:

- Understanding the effects of confounding factors such as screen size, communications delay, and sunlight readability.

- Learning how to create virtual representations of shape shifting robots (e.g., the PackBot) or robots with manipulators.
- Identifying whether robot health information should be displayed as part of the virtual UMV representation, or as a separate part of the display.
- Learning how to represent the intent of the UMV's autonomy.
- Coordinating the mixed reality displays with other display concepts such as those required to support multiple robots, semantic mark-up of the map, symbology, and display declutter.

6.5.2.4 References for Augmented/Mixed Reality Technology

- [1] Woods, D.D., Tittle, J., Feil, M. and Roesler, A. (2004, May). Envisioning human-robot coordination in future operations. *IEEE Transactions on Systems, Man, and Cybernetics, Part C*, 34(2), pp. 210-218.
- [2] Burke, J.L., Murphy, R.R., Coover, M.D. and Riddle, D.L. (2004). Moonlight in Miami: A Field Study of Human-Robot Interaction in the Context of an Urban Search and Rescue Disaster Response Training Exercise. *Human-Computer Interaction*, 19, 85-116.
- [3] Vicente, K.J., Christoffersen, K. and Pereklita, A. (1995, April). Supporting Operator Problem Solving Through Ecological Interface Design, *IEEE Transactions on Systems, Man, and Cybernetics*, 25(4), 529-545.
- [4] Milgram, P., Drascic, D., Grodski, J.J., Restogi, A., Zhai, S. and Zhou, C. (1995, February). Merging real and virtual worlds. *Proceedings of IMAGINA '95*.
- [5] Ricks, B.W., Nielsen, C.W. and Goodrich, M.A. (2004). Ecological displays for robot interaction: A new perspective. *International Conference on Intelligent Robots and Systems IEEE/RSJ, Sendai, Japan*.
- [6] Plumlee, M. and Ware, C. (2003). An evaluation method for linking 3D views. *Proceedings of the International Conference on Coordinated and Multiple Views in Exploratory Visualization*.
- [7] Goodrich, M.A., Rupper, R.J. and Nielsen, C.W. (August, 2005). Representing Head, Shoulders, Eyes and Toes in Augmented Virtuality Interfaces for Mobile Robots, To appear in *Proceedings of ROMAN*, Nashville, TN.
- [8] Quigley, M., Goodrich, M.A. and Beard, R.W. (2004, October). Semi-Autonomous Human-UAV Interfaces for Fixed-Wing Mini-UAVs. *Proceedings of IROS 2004, Sendai, Japan*.
- [9] Cooper, J.L. and Goodrich, M.A. (2005). Portable Mini-UAV Control Interfaces for Non-Pilots, Presented at the 2005 Human Factors of UAVs Workshop, May 25-26, 2006. Mesa, AZ.
- [10] Nielsen, C.W., Goodrich, M.A. and Rupper, R.J. (2005, August). Towards Facilitating the Use of a Pan-Tilt Camera on a Mobile Robot, To appear in *Proceedings of ROMAN*, Nashville, TN.
- [11] Pacis, E.B., Everett, H.R., Farrington, N., Sights, B., Kramer, T., Thompson, M., Bruemmer, D. and Few, D. (2005). Transitioning unmanned ground vehicle research technologies. *SPIE Proceedings*, 5804: Unmanned Ground Vehicle Technology VII.

- [12] Konolige, K. (2004). Large scale Map Building. Proceedings of the National Conference on AI, San Jose, CA.
- [13] Bruemmer, D.J., Marble, J.L., Few, D.A., Boring, R.L., Walton, M.C. and Nielsen, C.W. (2005, July). Let Rover Take Over: A Study of Mixed-Initiative Control for Remote Robotic Search and Detection, In: IEEE Transactions on Systems, Man, and Cybernetics Part-A: Special Issue on Human-Robot Interaction, 494-504.
- [14] Prinzel III, L.J., Comstock Jr., J.R., Glaab, L.J., Kramer, L.J. and Arthur, J.J. (2004). The Efficacy of Head-Down and Head-Up Synthetic Vision Display Concepts for Retro- and Forward-Fit of Commercial Aircraft. The International Journal of Aviation Psychology, 14(1), 53-77.
- [15] Schnell, T., Kwon, Y., Merchant, S. and Etherington, T. (2004). Improved Flight Technical Performance in Flight Decks Equipped with Synthetic Vision Information System Displays. The International Journal of Aviation Psychology, 14(1), 79-102.
- [16] Alexander, A.L. and Wickens, C.D. (2005). Synthetic Vision Systems: Flightpath Tracking, Situation Awareness, and Visual Scanning in an Integrated Hazard Display. In: Proceedings of the 13th International Symposium on Aviation Psychology. Oklahoma Cit, OK.
- [17] Draper, M.H., Nelson, W.T., Abernathy, M. and Calhoun, G. (2004). Synthetic vision overlay for improving UAV operations, Proceedings of the Association of Unmanned Vehicle Systems International Annual Symposium 2004, Baltimore MD.
- [18] Smallman, H.S. and St. John, M. (2005). Naïve Realism: Misplaced Faith in the Utility of Realistic Displays. Ergonomics in Design, Volume 13, Number 3.
- [19] CHEX (Change History Explicit): New HCI Concepts for Change Awareness. In: Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society, 528-532, Santa Monica, CA.
- [20] St. John, M., Manes, D.I., Smallman, H.S., Feher, B.A. and Morrison, J.G. (2004). Heuristic Automation for Decluttering Tactical Displays. In: Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting, New Orleans, LA.
- [21] Goodrich, M.A., Quigley, M. and Cosenzo, K. (2005). Task Switching and Multi-Robot Teams. Proceedings of the Third International Multi-Robot Systems Workshop, March 14-16, Washington, DC.
- [22] Quigley, M., Barber, B., Griffiths, S. and Goodrich, M.A. (2005). Towards Real-World Searching with Fixed-Wing Mini-UAVs. Proceedings of IROS 2005. August 2-6, Edmonton, Alberta, Canada.
- [23] Calhoun, G.L., Draper, M.H., Abernathy, M.F., Patzek, M. and Delgado, F. (2005). Synthetic Vision System for Improving Unmanned Aerial Vehicle Operator Situation Awareness. Proceedings of SPIE Vol. 5802, In: Enhanced and Synthetic Vision 2005, edited by Jacques G. Verly.

6.5.3 3D Visual Displays

Displayed information should fit the nature of the optimal mental processing operations required to perform the task. Wickens and Andre [1], Haskell and Wickens [2], and Wickens and Carswell [3] propose an interaction between the type of task performed and the type of display most suited for that task.

UAV supervisory control is an integrated task since the supervisor/operator must understand and combine location, angular, and rate of change information in 3D. Because 3D displays show the necessary information within a single spatial representation, it is proven that operator performance benefits more from these integrated 3D displays than from displays representing this spatial information in separate dimensions.

In this respect, we distinguish two types of 3D displays:

- 3D perspective displays. Perspective information may be considered as a subset of three-dimensional information (i.e., a stereoscopic image without binocular disparity).
- 3D stereoscopic displays. Stereoscopic displays are displays that create a true sense of depth.

6.5.3.1 Description of Technology

6.5.3.1.1 3D Perspective Displays

The graphical representation of the external world can be shown from the position of the observer, *egocentric* display information, or from a position somewhere in space, *exocentric* display information [4]). An egocentric presentation shows the external world only in one direction, suited to local guidance tasks, i.e., following a planned navigational track with limited preview. For example, when considering a flight task, pilots perceive themselves flying through the environment as seen from an ego-referenced frame [5]). This means that the display direction, left or right, always corresponds with the control direction. Exocentric displays separate the observer's eye point and actual position, showing the external world that surrounds the observer, thus assisting with global awareness. They represent the world either in a fixed geographical co-ordinate system (world-referenced; e.g., north up) or with respect to one's momentary position and orientation (ego-referenced; e.g., track up or heading up).

Research using egocentric perspective displays mainly has examined the navigation accuracy during local guidance tasks [6,7,8,9]. Research using exocentric perspective displays mainly focussed on world-referenced aspects: How effective will these displays support the situation awareness in a geographical environment? One study [10]) investigated the flight accuracy and orientation of pilots using two-dimensional (2D) plan-view, and 3D perspective north up, track up and heading up situation displays. Other investigations have examined pilots' perceptions of the geographical environment [11] and the assessment of collision risk [12]. Results have revealed that world-referenced exocentric displays can increase pilots' geographical orientation, but can hamper pilots' tracking performance in local guidance tasks because of the required mental transformations. For example, a north up display may cause confusion in an aircraft heading south [2,10]. Note that these investigations used more or less static scenarios. Ego-referenced exocentric display information, supporting the orientation of objects in space relative to the observer's momentary position, has hardly been a topic of much research activity. However, one may suppose that knowledge about the position of surrounding objects in space is of major importance.

Other research [13,14] has addressed methods of presenting perspective information on a display, investigating factors that influence the judgment of spatial information: grid-surface density, Geometric Field Of View (GFOV), Station Point Distance (STP), and target distance. It appeared that a perspective graphical presentation of the airspace provides a more natural (ecological) and compatible representation than a conventional plan-view display [15], but it was found difficult to estimate the exact position of computer-generated objects in that space. It is necessary, though, to carefully select the design parameters of the spatial information. For example, incorrect combination of GFOV and STP causes deformation of the presented image which leads to overestimation of the elevation angle [16].

Another important factor that affects the interpretation of perspective display information is scene dynamics during motion – the relative movement of the graphical components. In this respect, [17] distinguished motion references in avionic systems: with *inside-out* or ego-centered motion reference, the horizon rotates according to roll and pitch whereas the aircraft symbol remains stationary; and with *outside-in* or earth-centered motion reference, the horizon is stationary whereas the aircraft symbol rotates. Inside-out motion reference is compatible with the motion of the environment as it is observed from the cockpit; the aircraft is the reference, and the world is rotating. In contrast, outside-in motion reference shows the movements of the aircraft in a stationary world, representing the aircraft as a dynamic element in the real world. Research concerning the graphical representation of perspective display information as well as motion reference is reported here.

van Breda and Veltman [18] investigated 3D perspective displays in a simulated flight task. An aircraft guidance task was chosen with the following instruction: Perform a target acquisition task with a fighter aircraft, i.e., first locate a target that appears and then perform target interception (point the aircraft's nose toward the target as quickly as possible). For this task, it is of vital importance that pilots have correct estimations of the target's position, and of the route to be followed toward the target.

Egocentric displays are less suitable for this task because they provide only a limited view of the airspace in the flight direction. For high-quality task performance it is essential that the pilot obtain full preview, that is, being able to fully perceive the course of the stimulus (forcing function). Exocentric displays may meet this requirement, because targets beside or even behind are shown [19]. Both the display types were used in an experiment: an egocentric heading-up display for the initial aircraft following task (Figure 6-15) and an exocentric radar display for the interception task (Figure 6-16). Of the latter display, two types were investigated: a plan-view 2-D radar display, and a perspective 3D radar display. In the 2D display type, radar information consisted of an augmented circular plan-view display. The display centre represented the pilot's aircraft; a target symbol indicated the target position relative to the pilot's aircraft. The display was augmented with colour coding for relative target position, and a separate scale for target elevation was used. In the 3D condition, radar information consisted of an exocentric perspective spherical display, depicting the surrounding airspace as a dot pattern. Pilot's performance was analysed and evaluated in terms of target acquisition time, tracking performance and mental workload.

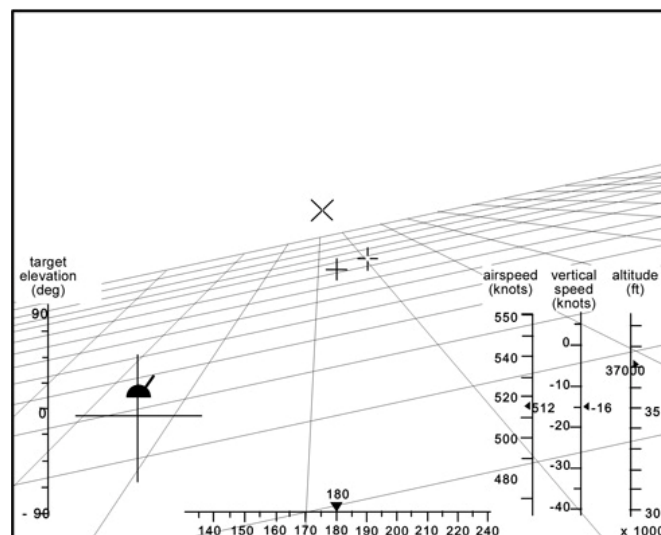


Figure 6-15: The Main Display.

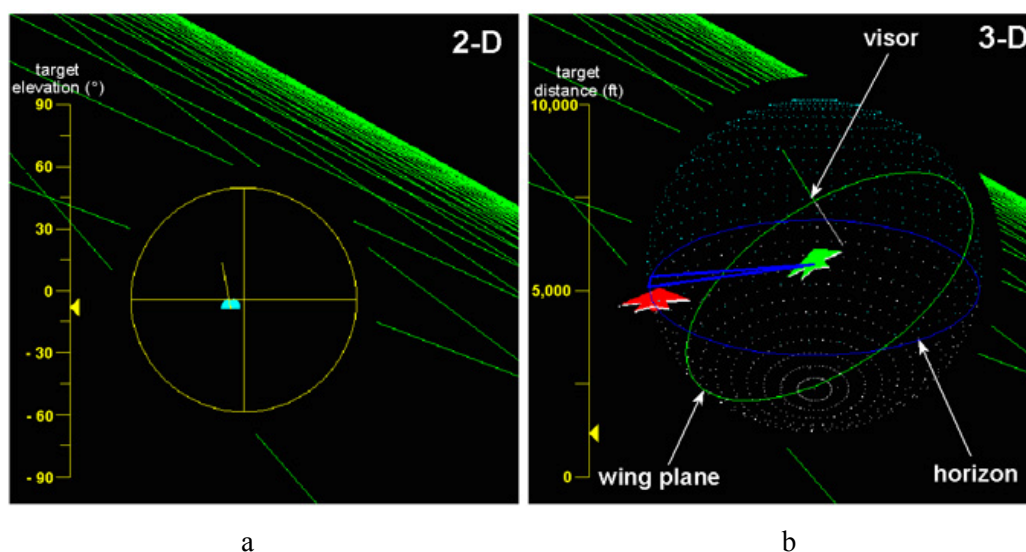


Figure 6-16: Overview of the Investigated Display Types.

The earth is represented by a grid, the target by an X symbol, the flight direction by a + symbol, and the length axis of the intercepting-aircraft by an _ symbol. Additional indicators for airspeed, vertical speed, altitude, and heading are shown. The radar display is presented in the lower left, in this case a two-dimensional plan-view radar image with an additional target elevation indicator.

The left figure shows a 2-D radar display with a separate target elevation indicator; the right figure shows a 3D radar display with a separate target distance indicator. The intercepting-aircraft symbol is always presented in the display centre. The line ahead, perpendicular to the wing plane, is the visor. Two 3D configurations were investigated: outside-in motion reference (the sphere with horizon and target symbol remain horizontal, whereas the intercepting-aircraft symbol rotates as a function of pitch and roll) and inside-out motion reference (the intercepting-aircraft symbol with wing plane remains horizontal, whereas the sphere with horizon and target symbol rotates as a function of pitch and roll). This figure shows a 3D radar display with outside-in motion reference.

The experimental results showed strong benefits of perspective displays for situation awareness support in the target acquisition task. A considerable reduction in the target acquisition time was obtained when pilots used a perspective radar display instead of a conventional plan-view display in the cockpit (Figure 6-17).

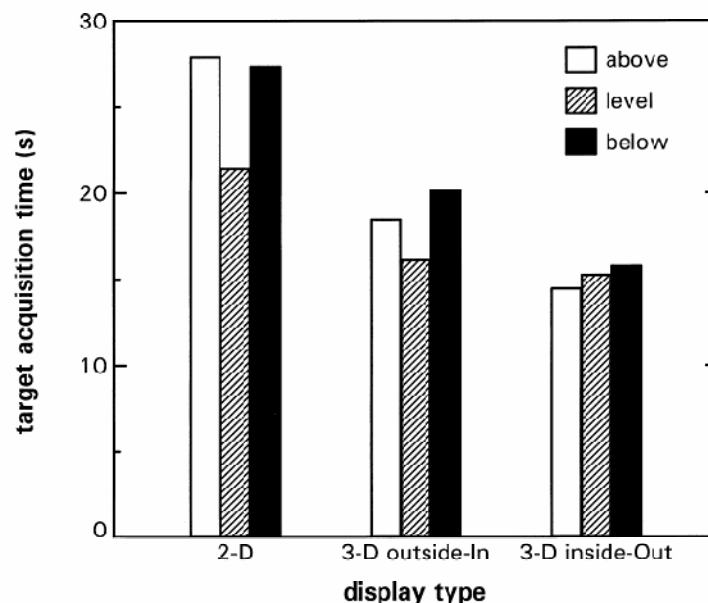


Figure 6-17: Target Acquisition Time as a Function of Two Dimensional (2-D) and Three Dimensional (3D) Display Type and Initial Position of the Target Aircraft, Averaged Across Participants.

This finding confirms one of the most important benefits of 3D perspective display representation as was observed by Wickens et al. [5]: The elimination of the time-consuming scanning that is necessary to go back and forth between the several parts of a display. In the 2-D display, a circular radar image indicating target azimuth and a separate linear indicator for the target elevation had to be scanned and mentally combined for target position estimation. In both the 3D perspective displays, target azimuth and elevation were presented in a single object. In the 3D perspective sphere, both the target elevation and target azimuth were integrated. For target acquisition, these variables represent information of close mental proximity.

Inside-out motion reference provided a direct relationship between the displayed movement of the scene and the perceived movements of surrounding objects. The display elements representing the outside world – three in this case – the sphere (globe) of the perspective radar display, the displayed horizon in the main (local guidance) display, and the visual horizon as seen from the cockpit, were consistent in this display, making the presented information ecologically valid [15,20]. The tracking task could therefore be considered as a natural process. The perspective sphere was presented by a dot pattern, providing adequate preview for tracking [21]. As was observed by [4]), 3D displays can be used very efficiently for local guidance tasks: in the current experiment the target acquisition time was reduced by more than 40%. It is obvious that this is a major improvement in performance.

The subjective effort scores showed almost the same pattern as the performance data. The pilots felt that less effort was needed when perspective displays were used; in particular, they felt more comfortable with the inside-out motion display.

The strongest motive to ‘go three-dimensional’ is the inability to combine the two dimensional ‘bird’s-eye view’ with a graphical presentation of altitude and depth information. As a consequence, in all current systems altitude and depth information is presented as numerical read-outs. Representations lacking integrated altitude and attitude information complicate situation assessment in two ways [22]. Data that are difficult to acquire

are more difficult to use in making a decision. Also, without immediately evident altitude information, a decision maker may substitute arbitrary or situation-biased altitudes, that may be difficult to supplant even when the actual data are presented. With more realistic images of the environment and tracks in a 3D perspective (see Figure 6-18), decision makers argue, the interface becomes more natural and less effort is required to comprehend the current situation. It eliminates the burden of integrating and interpreting of multiple representations, abstract symbols, and textual read-outs. Some earlier experimental results with perspective displays confirm these expectations.

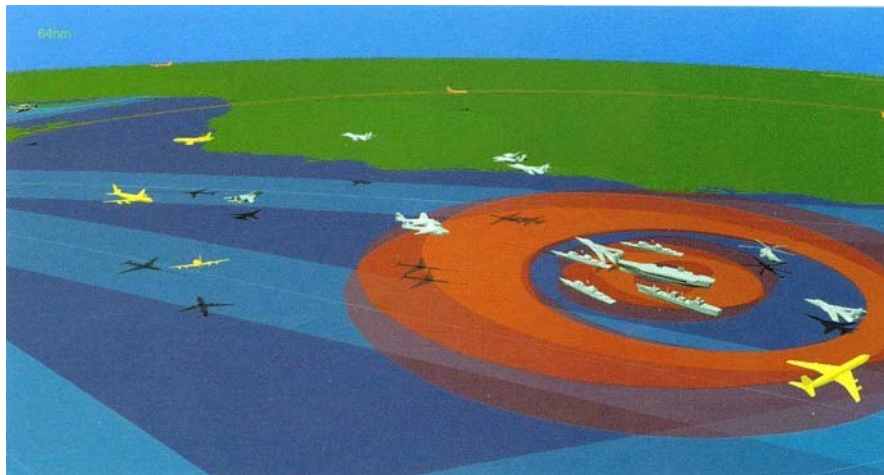


Figure 6-18: Example of a 3D Perspective Display (Adapted from Denehy, Johns Hopkins APL).

With the potential to improve performance, 3D perspective or stereoscopic displays, however, can also have their drawbacks. Inherent to the perspective view, objects are presented larger or smaller as a function of the operators viewing distance, location and angle. Objects close to the operator will be shown with much more resolution than objects at larger viewing distances. In many cases these differences will not necessarily reflect differences in tactical relevance and meaning. In their aspiration to design more realistic or natural representations of the environment researchers and software engineers also prefer to apply the principle of immersion to create the feeling of being part of that environment. Becoming embedded in the situation, however, can have some serious disadvantages. What you see becomes dependent on your own orientation. You have to look around not only to see what is happening miles away in front of you, but also what's happening directly behind your back. More realistic does not necessarily mean more functional.

One approach used at TNO is to let the environment become a 3D object in itself, such as a transparent cube that can be viewed from the outside and easily manipulated to see the environment from different perspectives and in different scales. In Figure 6-19, two pictures are shown that give an impression of this concept of a 3D tactical space. Simple geometric 2D and 3D symbols, comparable to the familiar naval tactical display symbology, are used to represent tracks.

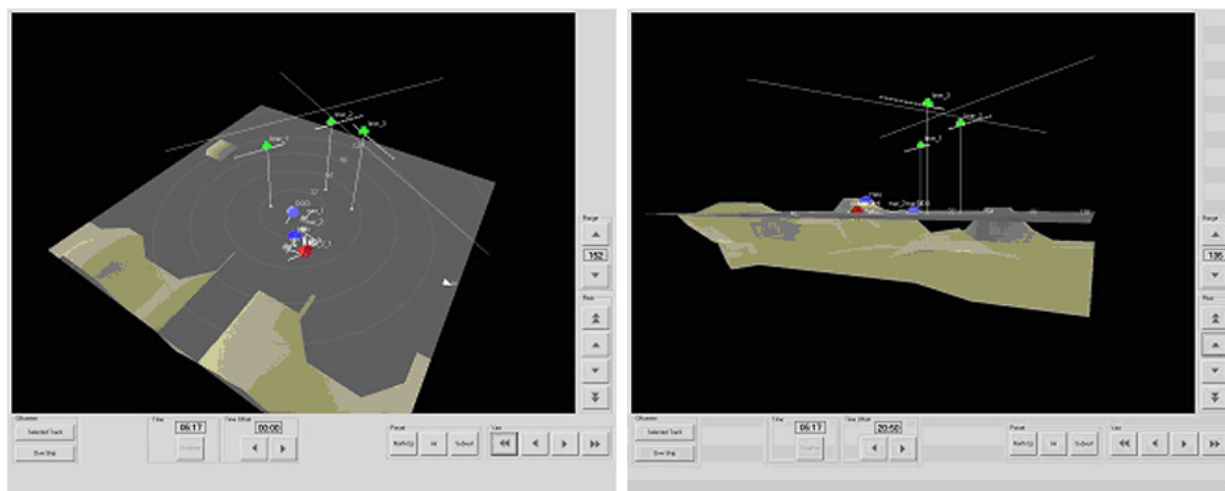


Figure 6-19: Examples of the Different Perspectives from which the Tactical Space Can be Viewed.

With one's own ship in the center of the tactical space as default, the operator has independent controls for horizontal and vertical zoom-in and zoom-out, to change the range or ceiling for which contacts are displayed. Size of symbols and track labels is held constant, irrespective of the zooming factor. With an off-center function, other tracks than the own ship can be selected to be presented in the center of the tactical space. By turning around and tilting the cube, the operator can view the environment from almost every perspective, be it air, surface or even subsurface, underwater. Independent of the selected perspective, all symbols and track labels remain in a steady orientation towards the user to guarantee good legibility. With a time-offset function the user can both playback or consult preceding moments in the situation and extrapolate the situation towards a future point in time. And dependent of platform type and armament, critical points in sensor and weapon coverage can be shown.

One of the most important functions of the tactical space is to have an environment that integrates information from different sources such as intel, traffic management, sensor and geographic information in a tactically meaningful way to support full situation awareness and assessment, especially when situations become less predictable or more complex as, for example, along the seashore. The concept of the tactical space, however, does not mean that all other ways of information display become superfluous, as confirmed in research done for the U.S. Navy [23]. There is no single display that can offer all information needed in an optimal way. The secret to good information presentation often lies in the diversity of multiple views on a situation and different graphical formats. With the tactical space well suited for the higher level tactical assessment, the 2D bird's eye view for instance, with its fixed orientation, more readily suits the fast localization of a track.

6.5.3.1.2 3D Stereoscopic Displays

Simply stated, 3D technology adds the sense of depth by imitating one or more of the visual depth cues. Here we describe how the 3D technologies achieve this result. A good overview can be found at the following website: <http://www.stereo3d.com/3dhome.htm>. More detail on the human factors aspects can be found elsewhere [24].

6.5.3.1.2.1 Convergence

Convergence can be activated by presenting (slightly) different images to the left and right eyes. The left-right difference is called the stereoscopic disparity. The most common methods are shutter glasses, polarized glasses, Red/Green glasses, and Head-mounted displays. They share the common disadvantage of constraining the user. Most importantly, eye contact is disturbed, hampering communication with others. These devices are therefore not well suited for group activities.

To avoid the constraints imposed by wearing optics in front of the eyes, so-called “auto-stereoscopic 3D displays” are being developed. The word “auto” signifies that the user does not need to wear an optical device. The optics are incorporated in the display, splitting the image in a left eye and a right eye component at the display instead. These optics are typically called “lenticular screens”, and are glued to the flat-panel display. A lenticular screen consists of small lenses that bend the light from different display pixels in different directions. An inherent feature of auto-stereoscopic displays is that the head needs to be positioned at the right place. If for example the right eye is shifted 6 cm to the left, it will see the left eye image. Though solutions exist that allow some freedom of head movement, a price is paid in terms of an increase in cross-talk which reduces the viewing comfort [25] or in terms of added complexity in the form of a head tracker [26]. For a comparison of 3D methodologies on visual comfort see [27]. The disadvantages of the four main techniques can be summarized as follows:

- Shutter glasses: low luminance, flicker in daylight environments
- Polarised glasses: need to keep the head straight up
- Red/Green glasses: no color vision, chromatic aberration, cross-talk
- HMDs: image moves with the head, cables or weight

In the next section, a fifth technique (transparency) will be described.

6.5.3.1.2.2 Pictorial Depth Cues

Displays that contain symbols are oftentimes incompatible with the use of monocular depth cues because these cues tend to interfere with the clarity and standardization of the symbols.

6.5.3.1.2.3 Accommodation and Parallax

The 3D displays described above simulate the convergence depth cue, but do not provide accommodation and parallax, which means that the depth percept is incomplete. Parallax can be added by tracking the head movements and adjusting the view point accordingly. However, even with a fairly powerful computer a time delay between head movement and image adjustment remains noticeable. Except for one prototype 3D display in Oxford [28], the accommodation cue can only be added by imaging the scene at physically different distances. The most advanced system is the U.S. Navy sponsored “volumetric display” which achieves the accommodation cue by imaging on a rotating drum [29]. However, its large volume (approximately 1 m³) makes it unsuitable for the type of applications we have in mind.

A relatively simple way to include accommodation and parallax in the depth percept is to optically superimpose two or more image slices through the scene. Such a transparent display presents “true depth” in the sense that all depth cues are present except for occlusion. An example transparent display is shown in Figure 6-20. A New Zealand Company [30] is the first to have marketed a compact transparent, 2-plane display. The display consists of two LCD filters, one placed in front of the other, making a subtractive

transparent display. Recently a 20-plane transparent display [31] has come on the market. We believe these developments to be highly significant, as argued in the next section.

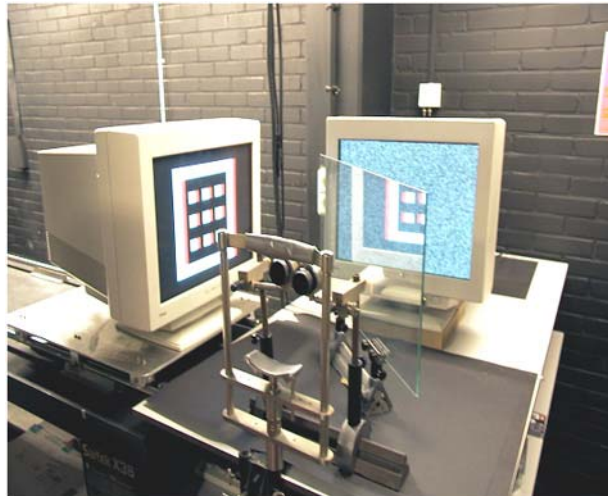


Figure 6-20: The Experimental Transparent 3D Setup at TNO Human Factors.

In Figure 6-20, two images are combined with a half-silvered mirror. Because the light from the two displays adds up, we call it an additive transparent display. The experiments examine the influence of various design parameters like amount of depth and scene content.

6.5.3.1.3 *Transparent Depth Displays*

6.5.3.1.3.1 Limited Number of Depth Planes

So far not much research has been done on transparent displays. This is probably because the limited number of depth planes makes them unsuitable for the display of 3D pictures and videos. The technologies described above can in principle present as many depth planes as the number of pixels in the display. We believe however that for professional applications involving the display of symbols, 2 or 3 depth planes will be sufficient to provide a large operational advantage. By analogy, many of the “full colour” cockpit displays by no means fully exploit their colour gamut; often a display only contains the four primary colours. Similarly the information content of control displays often times can be naturally divided into two (friend and foe) or three (above, below, and on the surface) layers. We therefore argue that the advantages of a transparent depth display will out-weigh the disadvantage of the limited number of depth planes.

6.5.3.1.3.2 Optimal Viewing Comfort and Depth Perception

In the case of transparent depth displays the depth percept is truly extra. The user does not pay a price in terms of resolution, colour, viewing angle, the need for special glasses, luminance, or viewing comfort as is the case with all other 3D displays. Secondly, our present research shows that the depth percept “pops-out” immediately while the other types of 3D displays require some amount of time for the depth percept to build up. Figure 6-21 shows how large the perceptual time delay is for unfavorable 3D stimuli. Thirdly, thanks to the parallax, occlusion of one object by another can easily be eliminated by moving the head sideways or vertically. This is important if two objects are located at the same x, y coordinates but different heights.

We therefore believe transparent planes to be very promising for the representation of computer generated data and symbols.

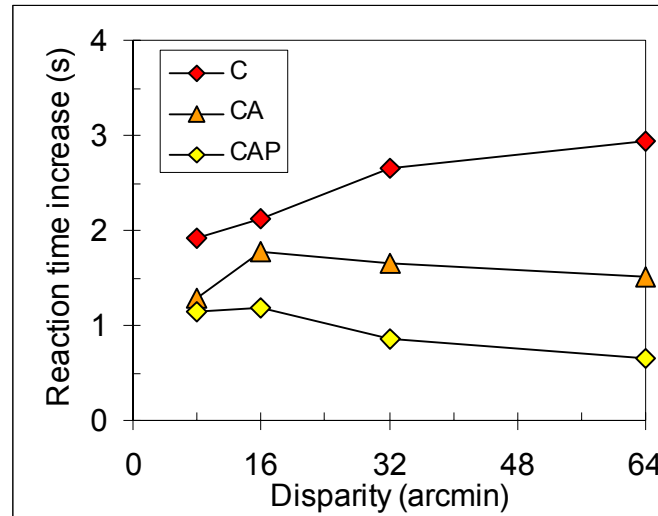


Figure 6-21: Data Substantiating the Claim that Accommodation (A) and Motion Parallax (P) Substantially Influences the Ease of Depth Perception when the Depth Gradient is Large.

Figure 6-21 shows the extra time required to perceive the depth relationship of two adjacent dots when a distracting object is added at a different depth. The horizontal axis contains the amount of depth difference. The increase in reaction time caused by the distractor is 1 to 2 seconds greater for the common type of 3D displays (C: Convergence cue only) than for transparent depth displays (CAP: accommodation and parallax as well as the convergence depth cue). These results imply that transparent depth displays are more natural to view than the standard 3D displays described in Chapter 3 and particularly suited for cluttered 3D imagery.

6.5.3.1.3.3 Subtractive and Additive Transparency

Another topic of current research at TNO Human Factors is design of the image content. We have shown that a transparent depth display, if designed wrong, can be very hard to fuse [32]. Secondly, the content of an additive transparent display (the front plane adds light: Figure 6-21) needs to be designed differently than a subtractive transparent display (the front plane removes light: e.g., Deepvideo [30]). The back layer of an additive display needs to be mostly dark, of a subtractive display mostly white. Otherwise the information in the other layer will not show up.

6.5.3.1.3.4 Occlusion

The 3D displays listed above do not fully show occlusion, the phenomenon that the front object 'hides' the back object. An additive 3D display however is not able to show occlusion and a subtractive 3D display only partially. In addition, colour mixing leads to erroneous mixed colours: the colour of the front object is influenced by the object behind and vice versa. For example, a yellow object on a purple background will appear as red on a subtractive 3D display (Figure 6-22). For any application involving warning symbols this is unacceptable and is at the expense of unwanted colour mixing. We therefore argue that only an additive +

subtractive transparent 3D display will support all the depth cues listed in Section 6.5.3.1.2. This may therefore well be the next major step forward in 3D technology.

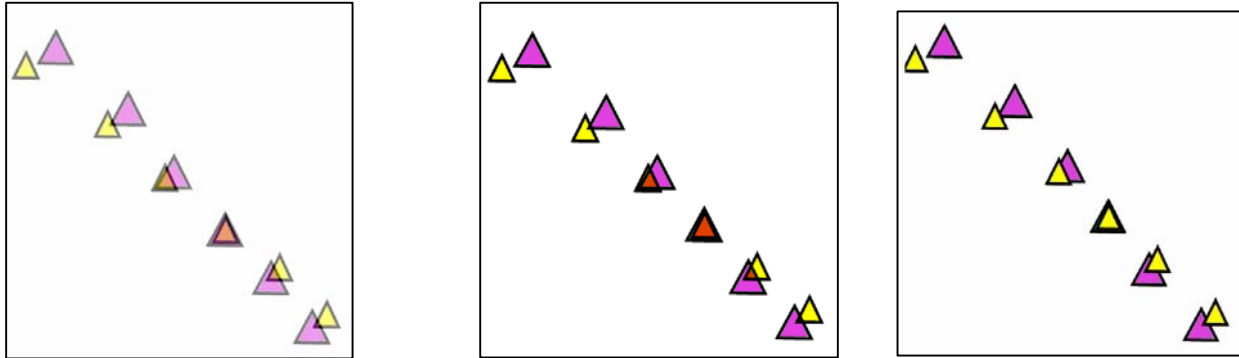


Figure 6-22: The Effect of Additive (left) and Subtractive (middle) Transparency: the Colours Combine, Easily Causing Confusion.

In this example yellow and purple combine to orange and red respectively. The picture to the RIGHT shows occlusion, the yellow triangles positioned in front occluding the purple triangles.

6.5.3.2 Actual or Potential Application to UMVs

De Vries and Jansen [33] developed a simulation environment in which human factors principles for UAV camera control are demonstrated and in which experimental studies are conducted. In an experiment they used this simulator environment to investigate the benefits of a 3D map with regard to operator performance and mental workload (Figure 6-23). They constructed a 2D map (oriented north-up) in which feedback about the control input was provided by means of an additional footprint that showed the predicted viewpoint of the camera. Operators were requested to find targets on roads and along wood edges. They could use the map to see to which part of the environment the camera was oriented. In one half of the conditions a 3D map was available together with the 2D map. The 3D map showed identical information, but was presented from the viewpoint of the camera. In some conditions, the quality of the camera images was manipulated by introducing a time delay of 1 second, or by lowering the update rate of the camera images to 3 Hz. This had no effect on the 2D and 3D map. Furthermore, in one half of the conditions a secondary task had to be performed. This was done to see whether operators had more spare mental capacity in case the 3D map was available. Several performance measures were taken. Workload was assessed using subjective and physiological measures.

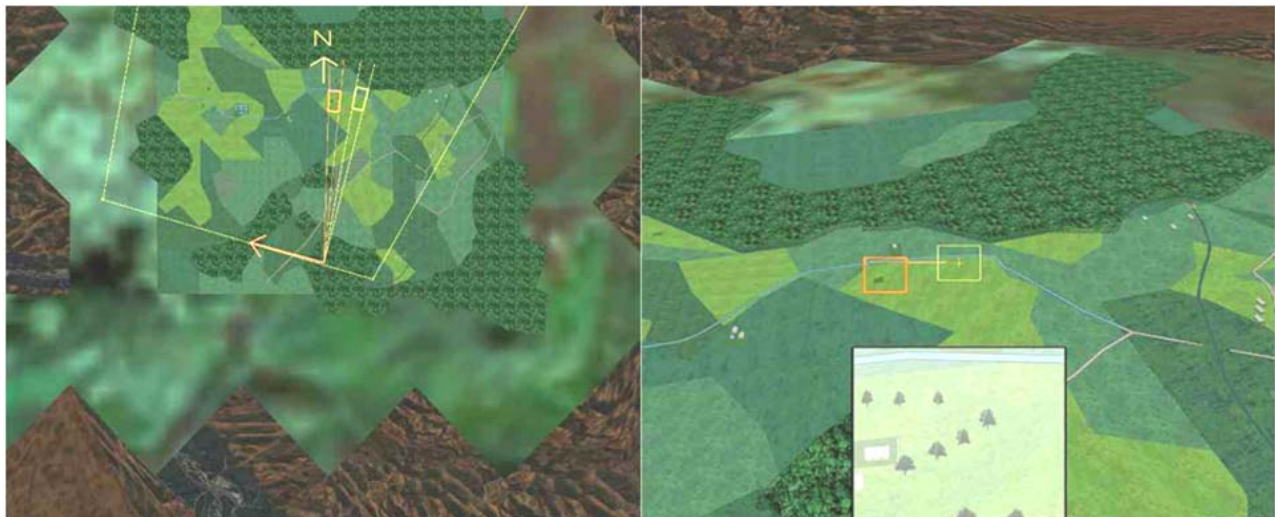


Figure 6-23: The Left Panel Shows the 2D Map with the Position of the UAV in the Center.

The right panel shows the 3D map, which is drawn from the viewpoint of the camera. In both displays, the yellow footprint shows the part of the environment that corresponds to the camera image and the orange footprint shows the predicted position based on operator input signals. The camera image is presented at the bottom of the right display.

The left panel of the simulator displayed a detailed 2D map of the environment, north-up oriented. Apart from terrain information (roads, woods, buildings, etc.) the following relevant information was presented: waypoints and the route of the UAV were shown (yellow line), flight direction of the UAV (orange arrow) and the actual and predicted footprints (see ‘Footprint’ below for an explanation). The right panel of the simulator displayed the 3D map, a virtual 3D world presented from the viewpoint of the UAV camera. The viewpoint for generating the 3D map depended on the camera control input of the operator, and the angular motion of this viewpoint was identical to the angular motion of the camera.

Both the 2D and 3D map showed a yellow footprint, representing the section of the map that corresponded to the camera images. The orange footprint provided direct feedback about the control input. In the conditions with low update rates and time delays, the yellow footprint followed the orange footprint. The size of the footprint could be adjusted by the zoom function, providing feedback about the zoom setting. With a zoom factor of 1, the size of the footprint on the right display was identical to the size of the camera panel. In conditions in which the 3D maps were not drawn on the right display, the footprints remained visible to provide feedback about the zoom settings.

The most important results of the experiment are presented here. The 3D map significantly improved task performance (Figure 6-24). A larger area was inspected, performance on secondary task improved, indicating that the participants had more spare mental capacity, and the participants reported lower effort.

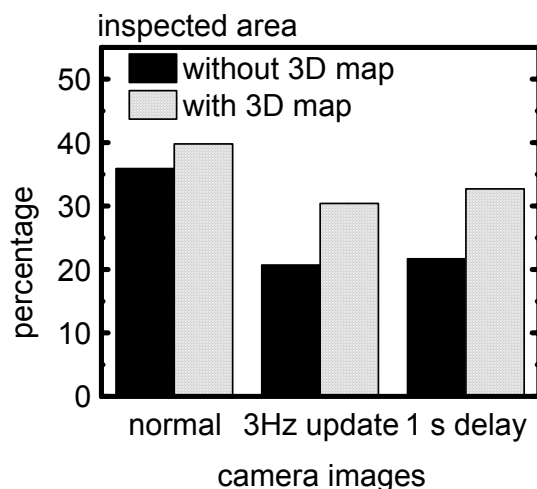


Figure 6-24: Percentage of Inspected Areas as a Function of 3D Map and the Quality of Camera Images.

The positive effect of the 3D map was largest when the quality of the camera images was low. Note that adequate feedback about time delays and low update rates was always available in both the 2D and 3D map display. Without this information, performance would be much worse in the conditions with low update rates and long time delay.

The subjective effort measure showed substantial effects as a function of all experimental factors (Figure 6-25), however, only heart rate showed a small effect as a function of the secondary task. This may be due to the lower sensitivity of physiological measures for mental effort. We found such discrepancies between subjective (Rating scale Subjective Mental Effort, RSME; [34]) and physiological measures more often [35] depending on the type of task that is evaluated. Participants most often give higher effort ratings when a task becomes more difficult as a result of a reduced quality of information.

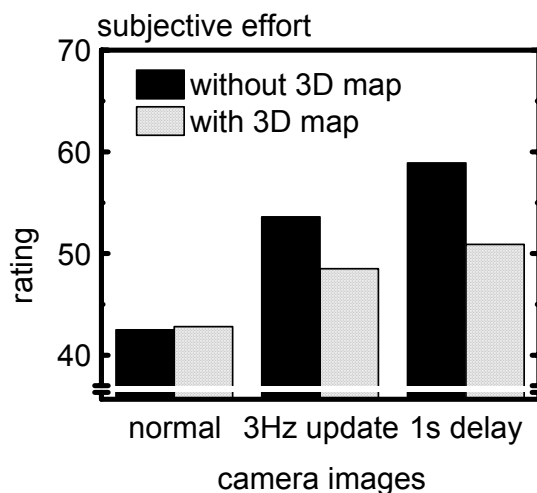


Figure 6-25: Subjective Effort Rating as a Function of Quality of the Camera Images and 3D Map.

Physiological measures most often do not show differences in these situations, because investing more effort most often will not result in better task performance. When an additional task has to be performed, attention has to be divided between more tasks. In these situations, additional effort has to be invested in order to keep an adequate level of performance of the main task. This is reflected in both subjective and physiological measures. The difference between the subjective and physiological measures can be explained along this line of thought. Degrading the quality of the display makes the task more difficult, resulting in higher effort ratings, but does not affect physiological measures because investing more effort will not improve performance. For the secondary task, more effort was required in order to maintain an adequate level of performance on the main task.

6.5.3.3 Technology Maturity, Challenges, and Unresolved Issues

3D perspective displays are used in a variety of applications. Current computing and graphic processing power allow applicability in near future UAV applications.

Although stereoscopic displays already exist in several forms, their application is still limited. The two primary bottlenecks are the associated lack of viewing comfort and the interference with other tasks. We argue that the construction of “transparent depth” displays is an important new development because it does not suffer from either of these two drawbacks. We believe the time is near to introduce transparent depth displays in professional environments like the cockpit, command and control workstations, vehicles, and hand-held devices.

6.5.3.4 References for 3D Visual Displays

- [1] Wickens, C.D. and Andre, A.D. (1990). Proximity compatibility and information display: Effects of color, space, and objectness on information integration. *Human Factors*, 32, 61-77.
- [2] Haskell, I.D. and Wickens, C.D. (1993). Two- and three-dimensional displays for aviation: A theoretical and empirical comparison. *International Journal of Aviation Psychology*, 3, 87-109.
- [3] Wickens, C.D. and Carswell, M. (1995). The proximity compatibility principle: Its psychological foundation and relevance in display design. *Human Factors*, 37, 473-494.
- [4] Wickens, C.D. and Prevett, T.T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays. *Journal of Experimental Psychology: Applied*, 1, 110-135.
- [5] Wickens, C.D., Liang, C., Prevett, T. and Olmos, O. (1994). Egocentric and exocentric displays for terminal area navigation. Savoy, IL: Aviation Research Laboratory.
- [6] Busquets, A.M., Parrish, R.V., Williams, S.P. and Nold, D.E. (1994). Comparison of pilot's acceptance and spatial awareness when using EFIS vs., pictorial display formats for complex, curved landing approaches. In: R.D. Gilson, D.J. Garland, and J.M. Coone (Eds.), *Situational awareness in complex systems* (pp. 139-170). Daytona Beach, FL: Embry-Riddle Aeronautical University Press.
- [7] Grunwald, A.J., Robertson, J.B. and Hatfield, J.J. (1980). Evaluation of a computer-generated perspective tunnel display for flight-path following (Tech. Rep. No. NASA TP1736). Langley, VA: National Aeronautics and Space Administration.
- [8] Roscoe, S.N. and Williges, R.C. (1975). Motion relationships in aircraft attitude and guidance displays: A flight experiment. *Human Factors*, 17, 374-387.

- [9] Theunissen, E. (1994). Factors influencing the design of perspective flight path displays for guidance and navigation. *Displays*, 15, 241-254.
- [10] Wickens, C.D., Liang, C., Prevett, T. and Olmos, O. (1994). Egocentric and exocentric displays for terminal area navigation. Savoy, IL: Aviation Research Laboratory.
- [11] Aretz, A.J. and Wickens, C.D. (1992). The mental rotation of map displays. *Human Performance*, 5, 303-328.
- [12] Ellis, S.R. and McGreevy, M.W. (1987). Perspective traffic display format and airline pilot traffic avoidance. *Human Factors*, 29, 371-382.
- [13] Ellis, S.R., Kim, W.S., Tyler, M., McGreevy, M. and Stark, L. (1985). Visual enhancements for perspective displays: Perspective parameters. *Proceedings of the International Conference on Systems, Man and Cybernetics* (pp. 815-818). New York: The Institute of Electrical and Electronics Engineers.
- [14] Barfield, W. and Young, K. (1991). Effect of geometric parameters of perspective on judgments of spatial information. *Perceptual and Motor Skills*, 73, 619-623.
- [15] Wickens, C.D. (1992). *Engineering psychology and human performance*. New York: Harper Collins.
- [16] McGreevy, M.W. and Ellis, S.R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. *Human Factors*, 28, 439-456.
- [17] Roscoe, S.N. and Williges, R.C. (1975). Motion relationships in aircraft attitude and guidance displays: A flight experiment. *Human Factors*, 17, 374-387.
- [18] van Breda, L. and Veltman, J.A. (1998). Perspective information in the cockpit as a target tracking acquisition aid. *Journal of Experimental Psychology: Applied*, 4, 55-68.
- [19] Stokes, A., Wickens, C.D. and Kite, K. (1990). *Display technology: Human factors concepts*. Warrendale, PA: Society of Automotive Engineers.
- [20] Andre, A.D., Wickens, C.D., Moorman, L. and Boschelli, M.M. (1991). Display formatting techniques for improving situation awareness in the aircraft cockpit. *International Journal of Aviation Psychology*, 1, 205-218.
- [21] Poulton, E.C. (1974). *Tracking skill and manual control*. New York: Academic Press.
- [22] Dennehy, M.T., Nesbitt, D.W. and Sumey, R.A. (1994). Real-time three-dimensional graphics display for antiair warfare command and control. *Johns Hopkins APL Technical Digest*, Volume 15, Number 2.
- [23] van Orden, K.F. and Broyles, J.W. (2000). "Visuospatial task performance as a function of two- and three-dimensional display presentation techniques". *Displays*, 21(1), 17-24.
- [24] Pastoor, S. (1993). Human factors of 3D displays, *Displays*, 14.
- [25] Philips. (2003). Philips 9 view auto-stereoscopic display, Website: <http://www.research.philips.com/generalinfo/special/3dlcd/index.htm>

- [26] SeeReal Technologies d4d. Website: <http://www.dresden3d.com> (2003).
- [27] Kooi, F.L. and Lucassen, M.P. (2001). Visual comfort of binocular and 3-D displays, In: B.E. Rogowitz and T.N. Pappas (Ed.), Human Vision and Electronic Imaging VI, pp. 586-592, The International Society for Optical Engineering, Bellingham, WA.
- [28] Eagle, R., Paige, E., Rogers, B. and Sucharove, L. (2000). Accommodation cues reduce latencies for large disparity detection. Poster presented at the European Conference on Visual Perception.
- [29] Soltan, P., Lasher, M., Dahlke, W., McDonald, M. and Acantilado, N. (1998). Improved second-generation 3-D volumetric display system, (Report SPAWAR Technical Report 1763), Space and Naval Warfare Systems Center, San Diego, CA.
- [30] Deep Video Imaging Ltd. (2003). Interactive dual plane imagery, Website: <http://www.Deepvideo.com>
- [31] 3dMedia. (2003). Multi-planer 3D volumetric display, Website: <http://www.3dmedia.com>
- [32] Schoumans, N., Kooi, F.L. and Hogervorst, M.A. (2003). Binocular fusion of transparent images, (Report in preparation), TNO Human Factors, Soesterberg, The Netherlands.
- [33] de Vries, S.C. and Jansen, C. (2002). Situational awareness of UAV operators onboard of moving platforms. Proceedings of the International Conference on Human-Computer Interaction in Aeronautics, pp. 144-147, HCI-Aero 2002 Cambridge, MA, 23-25 October 2002 (S. Chatty, J. Hansman, and G. Boy, Eds). Menlo Park, CA: AAAI Press.
- [34] Zijlstra, F.R.H. (1993). Efficiency in Work Behavior: a design approach for modern tools. Doctoral dissertation. Delft, The Netherlands: Delft University of Technology.
- [35] Veltman, J.A. and Gaillard, A.W.K. (1993). Physiological indices of workload in a simulated flight task. Biological Psychology, 42, 323-342.

6.5.4 Spatial Audio Displays

6.5.4.1 Description of Technology

Providing the appropriate information to support situation awareness is a primary challenge in the development of displays and controls for operators in any complex environment, but may be particularly challenging for the designer of interfaces for UMWs. A pilot in a traditional manned aircraft can directly perceive elements in the real world and may rapidly develop an understanding of the problem space by gleaning ambient information from peripheral factors including weather, terrain, and other vehicles in the airspace; he or she can maintain some level of understanding of the general vehicle status from displays in the cockpit, the auditory environment, and other crew members. However, many of these real-world cues are not as readily available to the operator of a UMW. Thus, the use of effective display technologies is critical to mission success.

Currently, UAV operator interfaces emphasize the presentation of information through visual displays. While often the most appropriate means for information conveyance, such systems run the risk of overloading the visual information processing capacity of the operator. The integration of display technologies focusing on other modalities affords the potential to reduce visual workload and display redundant cueing to provide for safeguards against undetected or unrecognized operationally meaningful information while also allowing for

synergistic relations to occur for the conveyance of higher-order information. Auditory display technologies, in particular, have shown great promise both as an information-bearing channel in isolation and as a component of an overall multi-modal display system. Audition excels as an early warning system – sound is inherently interpreted with respect to its signalling or warning significance. In addition, neural transmission in the auditory pathway is superior to that in the visual system, making it ideal for the display of time-critical warnings. The auditory system also plays a fundamental role in verbal communication, which is in many cases the most direct, efficient, and unambiguous means of information transfer. What is inherently appealing about these characteristics of the auditory system is that they are attention-demanding and serve to make the individual immediately aware of relevant elements in the situation. Moreover, the auditory system provides this information independent of the location of the event, for the auditory system monitors the environment from all directions at all times. Thus, information can be obtained about events in the environment even when they occur outside of the operator's visual field-of-view.

Although auditory displays do exist in most operational interfaces, they are rudimentary at best, and fail to leverage the natural spatial auditory processing capabilities of humans. That is, the ability of humans to determine the location of a sound source, monitor events at multiple locations simultaneously, and utilize auditory space as a means of organizing information, has not been fully exploited. Spatial auditory display technologies take advantage of the properties of the binaural auditory system by recreating and presenting to an operator the spatial information that would naturally be available in a "real-world" listening environment. Such displays are intuitive; they require little training and impose few additional demands on the information processing capacity of the operator.

The basic approach to generating spatialized (virtual) auditory displays assumes a "principle of equivalence" – that is, given that the display can generate a sound field at the eardrum that is identical to the sound field that would result from a real source, the perception should be equivalent to that for a real source. Thus, a virtual auditory display will result in the perception of sounds originating from real locations in space external to the listener's head.

The generation of virtual auditory displays is possible because of what is understood about the underlying mechanisms of spatial hearing and the cues that mediate sound localization. These cues arise as a result of the direction-specific, frequency-dependent modifications that are imposed on an incident waveform by a listener's head, torso, and pinnae as the sound travels from a source to a listener's eardrums. Two of these cues, interaural time differences (ITDs) and interaural level differences (ILDs), mediate sound localization in the left/right dimension. ITDs result from the fact that, due to path length differences, an acoustic waveform will arrive at the ipsilateral ear (i.e., ear nearest the sound source) earlier than at the contralateral ear (i.e., the ear on the side of the head opposite the sound source), leading to an interaural difference in time of arrival. Although these resulting interaural differences are small ($< 800 \mu\text{s}$), they are large relative to the temporal sensitivity of the auditory system, which can detect ITDs on the order of $10 \mu\text{s}$ [1]. Because of neural processing constraints, however, ITDs are primarily useful only in the low-frequency region (i.e., below about 1.5 kHz). For frequencies above approximately 3.0 kHz (a region in which the wavelength of an acoustic stimulus is small relative to the size a listener's head), the head casts an acoustic shadow such that the stimulus level at the contralateral ear is attenuated relative to the level at the ipsilateral ear. The resulting ILDs are useful for localizing sounds in this frequency region [2].

The interaural differences described above provide robust cues for sound localization in the left/right dimension; however, they are not sufficient to account for localization in elevation or front/back discrimination. Indeed, there are sets of locations, known as cones of confusion, which all produce the same interaural difference cues. A common result is that sounds will be localized to the wrong position

(e.g., the wrong elevation or front/back position) on the correct cone of confusion. The shape of the stimulus spectrum that reaches a listener's ears can help a listener disambiguate the location of a sound falling along a cone of confusion by providing cues regarding the elevation and front/back position of the sound. Narrowband spectral peaks and notches emerge from interactions between the stimulus and the pinnae in the frequency region above approximately 5.0 kHz (where the wavelength of the stimulus is small relative to the size of the pinna structures). These peaks and notches vary in relatively systematic ways as a function of elevation of the sound source, thus providing cues for localization in this dimension [3,4,5]. Additionally, each pinna casts an acoustic shadow such that a sound originating from a listener's rear hemifield will have relatively less energy in the 3.0 kHz to 6.0 kHz region than a sound originating in the frontal hemifield [6]. This filtering is presumed to help a listener resolve front/back confusions [7,8].

One additional cue that contributes to a listener's ability to determine the front/back location of a sound source arises from the fact that interaural difference cues change in predictable ways with head movement. For example, given a sound in the frontal hemifield, a clockwise rotation of the head will lead to ITDs and ILDs that indicate a sound moving to the left relative to the listener; a counter clockwise rotation in response to this same source will lead to the opposite experience. Listeners use these exploratory head movements to disambiguate the front/back location of a sound source.

All of these transformations that a waveform undergoes as it travels from a source to a listener's eardrums can be measured and captured in what is known as the head-related transfer function (HRTF; [9]). HRTFs can be measured by placing microphones in the left and right ear canals of a listener (or a mannequin head) and making recordings of broadband acoustic stimuli presented from a number of directions. Digital filters are constructed from these HRTFs and a virtual auditory stimulus can then be generated by convolving an arbitrary signal with the HRTFs for the left and right ear associated with a specific position in space. The result, when played back over headphones, is an experience in which the listener perceives the sound to have originated from that particular position in space. When done correctly, such a display can support sound localization performance that is equivalent to the localization of real sources in the free field [10]. Note that while virtual auditory displays can be delivered via loudspeaker systems instead of headphones, the veridicality of such displays is constrained by the size and acoustic characteristics of the room in which the display is presented. In addition, there is a relatively small region of space within a loudspeaker array over which a virtual auditory display will be valid for a listener. Thus, it is generally believed that headphone delivery of such displays is best. Such a practice allows the display designer to have complete control over the signal arriving at the listener's ears, independent of the conditions in which the display is presented.

In many situations, the spatial auditory display is required to present sounds that remain fixed in virtual space, independent of a listener's head movement. To accomplish this, the filters used to generate the virtual stimulus must be updated (in real-time) in response to the listener's head movement. This is achieved by continuously measuring the position of the listener's head using a head tracking system and providing this position information to the system responsible for rendering the spatial auditory stimuli. This system then convolves a sound with the filter associated with the appropriate location relative to the orientation of the listener at each point in time. Furthermore, because the HRTFs define a constrained set of discrete locations from which a virtual stimulus can be presented, an interactive display that includes head movement must be able to interpolate between sets of spatially adjacent HRTFs in order to present virtual stimuli from any arbitrary location.

A spatial auditory display with head tracking has a number of advantages. First, as discussed earlier, head movements can help a listener disambiguate the location of a sound source in the front/back dimension, thus improving localization performance. Similarly, such a display allows the listener to orient toward a

specific sound, bringing it into the “auditory fovea,” where spatial acuity is greatest. However, one of the greatest advantages of an interactive display is that it can be substantially more immersive than a static display because the auditory environment reacts in realistic and expected ways in response to a listener’s head movements. An interactive display is, in fact, necessary if one wishes to use virtual auditory stimuli to indicate the location of objects (such as targets and threats, as described below) in real space.

6.5.4.2 Actual or Potential Application to UMs

As previously stated, the development of displays to support situation awareness must be a primary goal of the designer for UMV operator interfaces. Situation awareness (SA) has been defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” [11]. From this, it has been suggested that SA may be more formally broken down into three component levels that can be independently addressed, studied, and measured. They are: Level 1 SA, which refers to the perception of elements in an environment within a particular volume of time and space; Level 2 SA, which pertains to the comprehension of the meaning of these elements; and Level 3 SA, which is concerned with the projection of the status of the elements in the near future.

If one considers the types of SA-related errors that occur in aviation mishaps within the context of the UMV operator environment, it is clear that spatial audio may offer significant utility at each level of SA. The SA Error Taxonomy [12] describes several reasons that situation awareness may break down within operational settings. Level 1 SA errors have been shown to account for 76% of aviation mishaps that are attributed to human error [13]. These errors could occur as a result of the lack of availability of required data or a failure of the system to present available data. Errors might also occur because the data are provided to the operator, but are difficult to detect or are merely not observed, not attended to, misperceived, or forgotten by the operator. Spatial auditory displays would likely benefit the operator in each of these situations.

The auditory system’s ability to serve as an early warning system, as well as its unique capacity for monitoring all locations simultaneously, can be exploited in spatial auditory displays. The auditory system is exquisitely sensitive to change, even when this change occurs outside of the current focus of attention. Changes associated with onsets (e.g., the introduction of new elements into a display) and offsets (e.g., the removal of an existing element from a display) are particularly well-detected. They are, in fact, often impossible to ignore, and drive the allocation of attention to elements in the environment that may yield critical information, thus reducing the chance that this information will go undetected. So natural is this phenomenon that several authors have suggested that the spatial auditory system evolved specifically to direct the visual system to meaningful events in the environment. Support for this hypothesis can be seen in laboratory studies involving visual search tasks, where spatially coincident auditory cues have been shown to reduce visual target acquisition and identification times by a factor of 2-5 in very simple visual scenes; much greater benefits have been found in more complex visual scenes such as those depicted in simulated operational environments [14,15,16]. Moreover, redundantly coding information using both auditory and visual stimuli may help to overcome systematic misperceptions. That is, the display of auditory information that is consistent with, and covaries with, visual information is not only unambiguous, but is consistent with operator expectancies, thus providing a more natural, intuitive interface. Given these issues, it seems clear that spatial audio cueing might be especially useful to UMV operators who are tasked with finding ground targets in a remote environment through the control of a maneuverable camera.

The success of future UMV systems will also depend on an operator’s ability to monitor multiple independent sources of information in order to maintain situation awareness. Here, again, the auditory modality is particularly well suited to the task, for the auditory system is capable of segregating multiple simultaneous

sounds into different streams [17], thus allowing an observer to attend to the most relevant information at any given time and to relegate the remaining information to the “background” for further processing when necessary. This ability to focus on certain information, while simultaneously and in parallel monitoring and maintaining a functional level of awareness about other sources of information, is invaluable in complex and dynamic operational environments. Because this segregation process is, in part, mediated by space [18], it can be exploited using spatial auditory displays.

One environment in which the utility of spatial audio for segregation has been extensively studied is that of the operator who must monitor multiple simultaneous communication channels. Here, substantial improvements in workload and communication effectiveness can be seen when the individual communication channels are presented such that they appear to originate from different locations in space, unlike standard monaural communication systems [19,20,21]. The flexibility of this display technology allows a user to configure the display such that particular communication channels are assigned to specific locations that are meaningful to the user. The UMV operator who must engage in verbal communications with a variety of distributed team members could make use of such a display to maintain an awareness of the identity of the specific talker from which each communication originated. That is, the operator can use space as an organizing principle, and this may result in enhancements of both Level 1 and Level 2 SA.

The appropriate development and comprehension of mental models necessary for achieving Level 2 SA may also be supported by an auditory environment in which the operator is immersed and experiences a sense of presence (i.e., “being there”). Support for this comes from the work of Ramsdell, who suggested that one function of the auditory system is to connect one to the real world on a primitive level, utilizing the incidental sounds that serve to make up the auditory “background.” [22]. This work was based on reports from suddenly-deafened individuals who reported that the world seemed “dead” and “(un)coupled,” that “it was almost impossible to believe in the passage of time ...couldn’t hear a clock tick” (p.503). Ramsdell distinguished this level of auditory perception from that of communication and warning, which are more obvious and overt functions of the auditory system, and suggested that this primitive level of perception is critical for a sense of “connectedness” to the world. This experience of suddenly-deafened individuals has been likened to that of the user of a virtual environment with an impoverished auditory display [23]. Perceptually rich virtual auditory environments are believed to lead to a strong sense of presence [24]. Although the link between presence and task performance is less clear [25] than that believed to exist between situation awareness and performance, it has been suggested that this is due in part to the lack of a robust measure of presence and/or the use of gross performance metrics that may not be sensitive to issues regarding how the interface is actually being used [26], and thus how the sense of presence may contribute to that usage. The sense of presence is concomitant with an engagement on the part of the operator, and this may be critical when the operator takes on a supervisory role over semi-autonomous UUVs. In this situation, there exists the potential that the operator will ‘fall out’ of the control loop and may have difficulty re-entering when necessary. Immersion in the virtual environment (i.e., the UUV operator interface) may facilitate intuitive interaction and ensure that the operator remains engaged in the mission even if not directly flying the vehicle.

Finally, the support of Level 3 SA may be assisted by an auditory display that is spatially, spectrally, and temporally dynamic. Information about the current and future states of highly-dimensional environments may be related via auditory information in a way that is engaging and intuitive. Operators may discern overall relationships and trends in order to better predict future states [27]. Auditory motion perception can be used to demonstrate trajectories of elements in the environment and are particularly compelling when used in conjunction with analogous visual displays for predicting future states, allowing the UUV operator to “fly several seconds ahead of the aircraft.” This temporal aspect of situation awareness may be particularly well-supported by a spatial auditory display.

6.5.4.3 Technology Maturity, Challenges, and Unresolved Issues

Many of the technological challenges that were considered in early iterations of spatial auditory displays have been largely overcome, the most obvious of which being adequate computational power. Increased memory capacity has allowed for the storage of a large number of measured HRTF locations, thus increasing the resolution of the rendered auditory space. Advances in digital signal processing capabilities have allowed for the rapid convolution of stimuli with more detailed representations of the HRTFs, and thus the presentation of increasingly complex auditory environments (e.g., multiple sources, room acoustics characteristics) that have the potential to yield richer and more compelling experiences for UMV operators.

Perhaps the greatest challenges that remain in the generation of veridical and compelling spatial auditory displays concern the psychoacoustic questions that continue to be of interest to auditory scientists. One issue concerns the fact that HRTFs are highly individualized, and it has been shown that the localization of virtual auditory stimuli is best when listening through one's own HRTFs. This is especially true for localization in those dimensions in which performance is mediated by spectral cues (i.e., elevation and front/back dimensions). However, because it is, in many cases, logistically impossible to collect HRTF measurements on each individual operator, the most common practice involves the use of generic HRTFs that were originally measured using a mannequin head. A better understanding of the relative importance of various spectral features for localization, and how these features are recovered by the auditory system, might allow for the construction of an effective set of non-individualized HRTFs. Such HRTFs could improve performance over existing generic models of auditory space and perhaps yield localization performance comparable to that found for free-field stimuli (i.e., greater accuracy, fewer front/back confusions, greater externalization of the auditory images).

Another issue that must be addressed in future developments of spatial auditory displays is the encoding of veridical sound source distance. For an arbitrary stimulus, there exist several acoustic cues that yield source distance information, among them sound source intensity, gross spectral characteristics, and the ratio of direct-to-reverberant acoustic energy reaching a listener [28,29]. It has been suggested that listeners utilize these cues when determining the distance of a remote sound source, thus dictating that such cues be incorporated into displays lest one provide impoverished distance information. In addition, in the auditory near field (i.e., less than 1 m from the head), distance perception is mediated in large part by characteristics in the HRTF that vary with source distance, in particular interaural level differences [30]. These cues appear to provide relatively salient cues about sound source distance, and thus should be implemented in future displays. However, auditory displays are likely to be used in noisy environments, and noise serves to disrupt localization cues not only in azimuth and elevation [31], but can also disrupt the cues for source distance by masking the reverberation and spectral cues in the display, and by reducing the dynamic range utilized for intensity-based distance coding. New symbologies must be developed that could be used in conjunction with existing cues to provide more reliable sound source distance. For example, one display that has been proposed [32] utilizes the effort with which a speech phrase is spoken to indicate distance – shouted speech indicates sources at greater distances, whispered speech indicates closer sources, and conversational speech indicates sources at distances in between.

It is important to note that spatial auditory displays have been integrated and tested in a number of operational environments including fighter jets and general aviation aircraft, as well as command and control centers [33,34]. The Air Force Research Laboratory has implemented a spatial audio display in two ground-based controller stations as part of a communications system upgrade at a training facility. This system, which allows users to allocate incoming voice communications to seven different apparent locations, has made it possible for dozens of operators to experience the advantages of spatial audio during the conduct of realistic

training missions. Operator feedback indicates that these spatial auditory displays allowed the operators to have “total SA” in the mission. Their comments indicate not only overwhelming acceptance by the user community, but also the increase in mission effectiveness that is possible due to the enhanced situation awareness supported by spatial audio. Spatial audio can therefore be classified as having a Technology Readiness Level of 8.

There are a number of unexplored applications for spatial audio that have the potential to enhance situation awareness for UMV operators. The need to monitor multiple simultaneous environments (e.g., the virtual operational environment and the real-world environment in which the operator station is located) may be supported by signal processing techniques employing room acoustics models to make the two categories of display elements appear to originate from different “rooms.” An auditory environment that is slaved to the UMV camera may allow the operator to unambiguously center a visual target in a complex visual scene that would otherwise be difficult to find. Spatial audio displays can also lead to a level of realism that as yet cannot be achieved in visual displays. Thus, they contribute substantially to a sense of presence and task engagement that could potentially improve overall operator performance. The challenge is to identify those specific features that contribute to presence and implement them. Nevertheless, in the nearly 20 years since the first functional spatial auditory display system was introduced, great advances have been made in both science and technology, resulting in a display that is reliable, mature, and cost-effective.

6.5.4.4 References for Spatial Audio Displays

- [1] Klump, R.G. and Eady, H.R. (1956). Some measurements of interaural time difference thresholds. *Journal of the Acoustical Society of America*, 28, 859-860.
- [2] Feddersen, W.E., Sandel, T.T., Teas, D.C. and Jeffress, L.A. (1957). Localization of high-frequency tones. *Journal of the Acoustical Society of America*, 29, 988-991.
- [3] Blauert, J. (1969/1970). Sound localization in the median plane. *Acustica*, 22, 205-213.
- [4] Butler, R.A. and Belendiuk, K. (1977). Spectral cues utilized in the localization of sound in the median sagittal plane. *Journal of the Acoustical Society of America*, 61, 1264-1269.
- [5] Middlebrooks, J.C. (1992). Narrow-band sound localization related to external ear acoustics. *Journal of the Acoustical Society of America*, 92, 2607-2624.
- [6] Shaw, E.A.G. (1974). Transformation of sound pressure level from the free field to the eardrum in the horizontal plane. *Journal of the Acoustical Society of America*, 56, 1848-1861.
- [7] Gardner, M.B. and Gardner, R.S. (1973). Problem of localization in the median plane: Effect of pinnae cavity occlusion. *Journal of the Acoustical Society of America*, 53, 400-408.
- [8] Oldfield, S.R. and Parker, S.P.A. (1984). Acuity of sound localization: A topography of auditory space. I. Normal hearing conditions. *Perception*, 13, 581-600.
- [9] Wightman, F.L. and Kistler, D.J. (1989a). Headphone simulation of free-field listening. I: stimulus synthesis. *Journal of the Acoustical Society of America*, 85, 858-867.
- [10] Martin, R.M., McAnally, K.I. and Senova, M.A. (2001). Free field equivalent localization of virtual audio. *Journal of the Audio Engineering Society*, 49, 14-22.

- [11] Endsley, M.R. (1988). Design and evaluation for situation awareness enhancement. Proceedings of the Human Factors Society 32nd Annual Meeting (pp. 97-101). Santa Monica, CA: Human Factors Society.
- [12] Endsley, M.R. (1995). A taxonomy of situation awareness errors. In: R. Fuller, N. Johnston, and N. McDonald (Eds.), Human factors in aviation (pp. 287-292). Aldershot, England: Ashgate Publishing Ltd.
- [13] Jones, D.G. and Endsley, M.R. (1996). Sources of situation awareness errors in aviation. *Aviation, Space, and Environmental Medicine*, 67, 507-512.
- [14] Bolia, R.S., D'Angelo, W.R. and McKinley, R.L. (1999). Aurally-aided visual search in three-dimensional space. *Human Factors*, 41, 664-669.
- [15] Simpson, B.D., Bolia, R.S., McKinley, R.L. and Brungart, D.S. (2005). The impact of hearing protection on sound localization and orienting behavior. *Human Factors*, 47(1), 188-198.
- [16] Bronkhorst, A.W., Veltman, J.A. and van Breda, L. (1996). Application of a Three-Dimensional Auditory Display in a Flight Task. *Human Factors*, 38, 23-33.
- [17] Bregman, A.S. (1990). Auditory scene analysis. Cambridge, MA: MIT Press.
- [18] Cherry, E.C. (1953). Some experiments on the recognition of speech, with one and two ears. *Journal of the Acoustical Society of America*, 25, 975-979.
- [19] Drullman, R. and Bronkhorst, A.W. (2000). Multichannel speech intelligibility and speaker recognition using monaural, binaural, and 3D auditory presentation. *Journal of the Acoustical Society of America*, 107, 2224-2235.
- [20] Brungart, D.S., Ericson, M.A. and Simpson, B.D. (2002). Design considerations for improving the effectiveness of multitalker speech displays. Proceedings of ICAD 2002 (pp. 424-430). International Community for Auditory Display.
- [21] Bolia, R.S., Nelson, W.T., Vidulich, M.A., Simpson, B.D. and Brungart, D.S. (2005). Communications research for command and control: Human-machine interface technologies supporting effective air battle management. Proceedings of the 10th International Command and Control Research and Technology Symposium. Washington: Command and Control Research Program.
- [22] Ramsdell, R.S. (1978). The psychology of the hard-of-hearing and the deafened adult. In: H. Davis and S.R. Silverman (Eds.), *Hearing and deafness* (4th ed., pp. 499-510). New York: Holt, Rinehart & Winston.
- [23] Gilkey, R.H. and Weisenberger, J.M. (1995). The sense of presence for the suddenly deafened adult. *Presence*, 4, 357-363.
- [24] Gilkey, R.H., Simpson, B.D. and Weisenberger, J.M. (2001). Creating Auditory Presence. Proceedings of the HCI 2001 International Conference, New Orleans, 609-613.
- [25] Welch, R.B. (2000). How can we determine if the sense of presence affects task performance? *Presence: Teleoperators and Virtual Environments*, 9, 574-577.

- [26] Kalawsky, R.S. (2000). The validity of presence as a reliable human performance metric in immersive environments. Proceedings of the 3rd International Workshop on Presence, Delft, The Netherlands.
- [27] Kramer, G. (1994). An introduction to auditory display. In: G. Kramer (Ed.), Auditory display: Sonification, audification, and auditory interfaces (pp. 1-77). Reading, MA: Addison-Wesley.
- [28] Zahorik, P. (2002). Auditory display of sound source distance. Proceedings of the 2002 International Conference on Auditory Display.
- [29] Bronkhorst, A.W. and Houtgast, T. (1999). Auditory distance perception in rooms. *Nature*, 397, 517-520.
- [30] Brungart, D.S. and Rabinowitz, W.M. (1999). Auditory localization of nearby sources. Head-related transfer functions. *Journal of the Acoustical Society of America*, 106, 1465-1479.
- [31] Good, M.D. and Gilkey, R.H. (1996). Sound localization in noise: The effect of signal-to-noise ratio. *Journal of the Acoustical Society of America*, 99, 1108-1117.
- [32] Brungart, D.S. (2000). A speech-based auditory distance display. Proceedings of the 109th Convention of the Audio Engineering Society, 22-25.
- [33] McKinley, R.L. and Ericson, M.A. (1997). Flight demonstration of a 3-D auditory display. In: R.H. Gilkey and T.R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments* (pp. 683-699). New Jersey: Lawrence Erlbaum Associates.
- [34] Simpson, B.D., Brungart, D.S., Dallman, R.C., Joffrion, J., Presnar, M.D. and Gilkey, R.H. (2005). Spatial audio as a navigation aid and attitude indicator. Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, 1602-1606.

6.5.5 Haptic Display Technology

6.5.5.1 Description of Technology

Designers of human machine interfaces are increasingly applying multi-modal interfaces. An important reason for this is the need for an alternative or complementary information channel in complex operator environments [1,2,3]. Traditionally, the auditory channel is often considered as an alternative or supplement to visual displays. Examples include the presentation of route navigation [4,5] and tracking error information [6,7]. However, there are situations in which the visual and auditory channels of an operator are both heavily loaded or in which the visual and/or auditory information is degraded. In those situations, a haptic display system may be useful.

An example of a tactile display is the TNO tactile waist belt (Figure 6-26). The tactile display consists of eight vibrating elements (1.3 V vibrating DC motors, housed in rectangular PVC boxes) with a body contact area of 1.5 by 2.0 cm and a vibration frequency of 155 Hz. The boxes are mounted in an adjustable waist belt. The resolution of the displays (i.e., 8 factors for 360°) is in between the minimum required (i.e., two elements: one for left and one for right) and the limit of direction perception on the torso (to be in the order of 10°). The location of the elements in the belt is adjustable so they can easily be positioned in the direction of the cardinal and oblique axes irrespective of the body form of the person who is wearing the belt. The waist belt is worn over the underclothing of the person.



Figure 6-26: Example Tactile Display (Tactile Waist Belt Clearly Showing the Vibration Elements).

Another example is the tactile torso display. TNO [8,9] used a torso display consisting of 64 vibro-tactile elements that presented information concerning the desired direction of motion (simple version), and a torso display that included information concerning an actual motion direction (complex version). Figure 6-27 shows such a torso display used in experiments based on helicopter scenarios.



Figure 6-27: Example of a Tactile Torso Display Used in Helicopter Orientation Studies [21].

6.5.5.2 Actual or Potential Application to UMVs

6.5.5.2.1 Vibrotactile Displays

Vibrotactile displays present information by delivering a localised vibration to the skin. Partly due to the trends in multi-modal interfaces, this kind of display is going through a rapid development. Although the technology to build active displays was already developed 40 years ago, the applications were mainly restricted to research tools. An important example is the TVSS, a device developed by Bach-y-Rita and

colleagues that displays visual information acquired by a camera on a 144-element vibrotactile display attached to the abdomen of the observer [10]. Today, cellular phones with vibration function are probably the best-known example of a tactile display, but many examples of tactile displays are also developed within the military domain. In relation to UAVs, tactile displays are receiving a small share of interest, as far as we know they are only investigated in several laboratories, but are not on the market yet.

We will discern the following two areas in which adding a tactile display to the UMV-operator interface may be beneficial.

- a) (Directional) warning/attention allocation system. The vibration function on a mobile phone and the stick shaker, which warns pilots that the aircraft is in danger of stalling, are two examples of a tactile warning system. Experimental evidence that indicates that vibrotactile displays are well suited to detect time critical events is provided by several authors. For example, Martens and Van Winsum [11] found that tactile warning cues were more effective than speech warning cues in presenting collision avoidance warnings. Sklar and Sarter [12] demonstrated that the use of tactile cues for indicating unexpected changes in status are more effective than visual cues. Additionally, some research has been conducted on the usefulness of vibrotactile displays within UAV control applications [13,14,15]. The UAV operator wore small tactors mounted in elastic bands, one on each inner wrist (Figure 6-28). When a high priority system contingency occurred, one or both of the tactors vibrated. By noting which tactor(s) was vibrating, the operator could rapidly identify the system that needs attention, especially when attention was directed to a display not containing a visual warning. This technology has strong potential for directing attention to unexpected events in future UMV control environments where the operator supervises automated systems.



Figure 6-28: Tactile Wrist Pads as High Priority Alert Cue.

- b) Spatial information. This category is of special interest to UMV applications and also the area that receives attention for military applications. Since the nineties, the tap-on-the-shoulder principle is implemented in tactile torso displays. The power behind this concept is that the proverbial tap on shoulder draws and directs the spatial attention of the observer. Displays that can provide this tap on any location on the torso and that consider the torso as a 3D sphere are able to project 3D spatial information directly and intuitively. Several preconditions for successful application of this principle have been fulfilled, e.g., the spatial resolution and the accuracy of direction perception have been investigated [16], as are the effects of applying the principle in dynamic environments and in combination with other sensory modalities [17,18]. Proof-of-concept studies also show encouraging results for helicopter hover tasks [19,20,21], spatial disorientation situations [22,23,24], waypoint navigation [16] and vehicle control [24,25]. In UVMs, acquiring spatial information or a good sense of spatial awareness is one of the critical issues. For example, the multiple frames of reference for an operator (especially a moving operator, i.e., an operator that is on board a moving platform) may slow

down this process and the quality of the decisions made. A tactile display that uses the tap-on-the-shoulder principle can be a powerful situation awareness support [26,27,28], for instance by presenting the heading direction of the vehicle.

6.5.5.2.2 Force Feedback Displays

Force feedback (proprioceptive) displays present information via forces on the controls. Force feedback devices can be used in a general human-computer interaction setting (e.g., a force feedback mouse or rollerball), but are not particularly widespread. On the other hand, force feedback joysticks and steering wheels are quite common in gaming. Also, force displays have proven their value in many remote control situations. In UMVs, force feedback devices can also be of use, amongst others because the control of their inhabited equivalents relies on these devices. For example, in road vehicles, forces (and vibrations) in the steering wheel provide important information about the road conditions as well as the vehicle behaviour. The same holds for forces in flight controls of helicopters and airplanes. Especially when the UMV is controlled in the loop, this information may be of great value. Force displays may also assist operators in camera control tasks, for example by presenting platform motions via joystick motions or forces [29,30].

Wind turbulence is potentially detrimental to safe and effective UAV tele-operated control. Unfortunately, the physical separation of the crew from the aircraft makes detection of sudden turbulence onset very difficult, often solely indicated by an unexpected perturbation of video images transmitted from a UAV mounted camera. One study [31] explored how to provide the UAV pilot with an enhanced indication of turbulence. Four different alerts were evaluated: Visual (perturbation of nose-camera imagery and overlaid HUD symbology – Baseline), Visual/Haptic (Visual and additional 1 second, low gain, high frequency vibration of the control stick using an Immersion Corporation 2000 Force Feedback Joystick), Visual/Aural (Visual and 1 second pure tone), Visual/Aural/Haptic (all three cues simultaneously). Data were collected from pilots as they performed simulated landing tasks. Conditions containing the haptic cue (Visual/Haptic and Visual/Haptic/Aural) resulted in less error than non-haptic cue conditions (Visual and Visual/Aural). Although the aural alert also improved landing accuracy and detection of turbulence direction, performance was best with the redundant kinesthetic feedback. When randomly queried regarding the primary direction of the UAV immediately following a turbulence event, participants were more accurate when haptic feedback had been present. It should be noted that the operators commented that only a slight haptic feedback is required (and desired) to alert turbulence onset.

6.5.5.3 Technology Maturity, Challenges, and Unresolved Issues

The technology for haptic feedback is very mature, though experiments designed to determine the effectiveness of haptic information for military applications are on-going. Early studies show promise for the effective use of this technology, with practical military applications on the near horizon.

6.5.5.4 References for Haptic Display Technology

- [1] Spence, C. and Driver, J. (1997). Cross modal links in attention between audition, vision, and touch: implications for interface design. *International Journal of Cognitive Ergonomics*, 1 (4), 351-373.
- [2] Wickens, C.D. and Hollands, J.G. (2000). Attention, time-sharing, and workload. Chapter 11 in *Engineering Psychology and Human Performance*. NY: Prentice Hall.
- [3] Wickens, C. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, 3, 2, 159-177.

- [4] Parkes, A.M. and Coleman, N. (1990). Route guidance systems: A comparison of methods of presenting directional information to the driver. In: E.J. Lovesey (Ed.), *Ergonomics – Setting standards for the ‘90’s*. London: Taylor & Francis, pp. 480-485.
- [5] Streeter, L.A., Vitello, D. and Wonsiewicz, S. (1986). How to tell people where to go: comparing navigational aids. *International Journal of Man-Machine Interaction*, 22, 549-562.
- [6] Forbes, T.W. (1946). Auditory signals for instrument flying. *Journal of Aeronautical Science*, 13, 255-258.
- [7] Wickens, C.D. (1992). *Engineering psychology and human performance*. New York: Harper Collins.
- [8] van Erp, J.B.F. (2005). Presenting Directions with a Vibro-Tactile Torso Display. Accepted by *Ergonomics*.
- [9] van Erp, J.B.F., Groen, E.L., Bos, J.E. and Van Veen, H.A.H.C. (2005). A Tactile Cockpit Instrument Supports the Control of Self-Motion During Spatial Disorientation. *Human Factors*.
- [10] Bach-y-Rita, P., Collins, C.C., Saunders, F., White, B. and Scadden, L. (1969). Vision substitution by tactile projection. *Nature*, 221.
- [11] Martens, M.H. and Van Winsum, W. (2001). Effects of speech versus tactile support messages on driving behaviour and workload. *Proceedings of the 17th International Technical Conference on Enhanced Safety of Vehicles*, Amsterdam.
- [12] Sklar, A.E. and Sarter, N.B. (1999). Good vibrations: tactile feedback in support of attention allocation and human automation coordination in event-driven domains. *Human Factors*, 41 (4), 543-452.
- [13] Calhoun, G.L., Draper, M.H., Ruff, H.A. and Fontejon, J.V. (2002). Utility of a tactile display for cueing faults. *Proceedings of the Human Factors and Ergonomic Society 46th Annual Meeting* (pp. 2144-2148), Santa Monica, CA: Human Factors and Ergonomic Society.
- [14] Calhoun, G.L., Draper, M.H., Ruff, H.A., Fontejon, J.V. and Guilfoos, B. (2003). Evaluation of tactile alerts for control station operation. *Proceedings of the Human Factors and Ergonomic Society 47th Annual Meeting* (pp. 2118-2122), Santa Monica, CA: Human Factors and Ergonomic Society.
- [15] Calhoun, G.L., Ruff, H.A., Draper, M.H. and Guilfoos, B.J. (2005). Tactile and aural alerts in high auditory load UAV control environments. *Proceedings of the Human Factors and Ergonomic Society 49th Annual Meeting* (pp. 145-149), Santa Monica, CA: Human Factors and Ergonomic Society.
- [16] van Erp, J.B.F., van Veen, H.A.H.C., Jansen, C. and Dobbins, T. (2005). Waypoint Navigation with a Vibrotactile Waist Belt. Accepted by *Transactions on Applied Perception*.
- [17] van Erp, J.B.F. and Werkhoven, P.W. (2004). Vibro_tactile and visual asynchronies: Sensitivity and consistency. *Perception*, 33, 103-111.
- [18] van Erp, J.B.F. and Verschoor, M.H. (2004). Cross-Modal Visual and Vibro-Tactile Tracking. *Applied Ergonomics*, 35, 105-112.

- [19] Rupert, A.H. (2000). An instrumentation solution for reducing spatial disorientation mishaps. *IEEE Engineering in Medicine and Biology*, 19, 71-80.
- [20] Rupert, A.H. (2000). Tactile situation awareness system: proprioception prostheses for sensory deficiencies. *Aviation Space and Environmental Medicine*, 71, A92-A99.
- [21] van Erp, J.B.F., Veltman, J.A., Van Veen, H.A.H.C. and Oving, A.B. (2003). Tactile Torso Display as Countermeasure to Reduce Night Vision Goggles Induced Drift. *Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures. RTO Meeting Proceedings*, 86, pp. 49-1 – 49-8. Neuilly-sur-Seine Cedex, France: NATO RTO.
- [22] Rupert, A.H., Guedry, F.E. and Reschke, M.F. (1993). The use of a tactile interface to convey position and motion perceptions. *AGARD meeting proceedings on 'Virtual interfaces: research and applications'*. Neuilly-sur-Seine, France: RTO NATO.
- [23] Benson (2003). Technical Evaluation Report. *Spatial disorientation in military vehicles: causes, consequences and cures. RTO Meeting Proceedings 86*. Neuilly-sur-Seine Cedex, France: NATO RTO.
- [24] van Erp, J.B.F. and Van Veen, H.A.H.C. (2004). Vibrotactile in vehicle navigation system. *Transportation Research, Human Factors*, 7, 247-256.
- [25] Dobbins, T. and Samway, S. (2002). The use of tactile navigation cues in high-speed craft operations. *Proceedings of the RINA Conference on High Speed Craft: technology and operation*, pp. 13-20. London: The Royal Institution of Naval Architects.
- [26] Gilliland, K. and Schlegel, R.E. (1994). Tactile stimulation of the human head for information display. *Human Factors*, 36 (4), 700-717.
- [27] Raj, A.K., Kass, S.J. and Perry, J.F. (2000). Vibrotactile displays for improving spatial awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Santa Monica, CA: The Human Factors and Ergonomics Society, pp. 181-184.
- [28] Raj, A.K., McGrath, B.J., Rochlis, J., Newman, D.J. and Rupert, A.H. (1998). The application of tactile cues to enhance situation displays. *3rd Annual Symposium & Exhibition on Situational Awareness in the Tactical Air Environment*, (pp. 77-84). Patuxent River, MD.
- [29] Korteling, J.E. and Van der Borg, W. (1997). Partial camera automation in an unmanned air vehicle. *IEEE Transactions on Man and Cybernetics A*, 27 (2), 256-262.
- [30] Korteling, J.E. and Van Emmerik, M.L. (1998). Continuous haptic feedback in target tracking from a moving platform. *Human Factors*, 40 (2), 198-208.
- [31] Draper, M.H., Ruff, H.A., Repperger, D.W. and Lu, L.G. (2000). Multi-sensory interface concepts supporting turbulence detection by UAV controllers. *Proceedings of the Human Performance, Situational Awareness and Automation Conference* (pp. 107-112). Savannah Georgia.

6.6 INTERFACE ISSUES FOR MULTI-UMV SUPERVISORY CONTROL

6.6.1 Implications of Automation/Autonomy

6.6.1.1 What is Automation and Supervisory Control?

A common frame of reference is needed to discuss automation and subsequently supervisory control. The Oxford Dictionary of Current English [1] defines automation as “use or introduction of automatic methods or equipment in place of manual labour.” Thus, automation takes place when a task that is usually performed by a human is performed by a machine (often a computer). An automatic transmission on a car, for example, takes the place of a human physically shifting the gears, and automates this task. The process by which the human controls the automated system (i.e., selecting the appropriate gear) is supervisory control [2]. This section will focus on the interaction between automation and supervisory control or more specifically, the interface implications posed by automation.

Automation is not all or none. It comes in many forms and varieties and has been characterized as levels of automation or supervisory control. Sheridan and Verplank [3] proposed one of the first automation taxonomies characterized by eight levels of supervisory control (Table 6-1).

Table 6-1: A Scale of Degrees of Automation (Sheridan and Verplank, 1978)

1	The computer offers no assistance; the human must do it all.
2	The computer suggests alternative ways to do the task.
3	The computer selects one way to do the task and executes that suggestion,
4	if the human approves, or
5	allows the human a restricted time to veto before automatic execution, or
6	executes automatically, then necessarily informs the human, or
7	executes automatically, then informs the human only if asked.
8	The computer selects the method, executes the task and ignores the human.

More recently Parasuraman, Sheridan and Wickens [4] developed a framework for making decisions on what functions should be automated and to what extent. Four classes of function were proposed:

- 1) Information acquisition;
- 2) Information analysis;
- 3) Decision and action selection; and
- 4) Action implementation.

Automation can vary within each function from low to high (see Table 6-2) and a particular system can be automated at different levels in each of the four functions. The model then presents a methodology for deciding what level of automation should be assigned what level of automation for a particular system. This methodology is based on primary criteria; mental workload, situation awareness, and complacency, as well as secondary criteria: automation reliability and costs of decisions/outcomes.

Table 6-2: Levels of Automation of Decision and Action Selection [4]

HIGH	10	The computer decides everything, acts autonomously, ignoring the human.
	9	informs the human only if it, the computer, decides to
	8	informs the human only if asked, or
	7	executes automatically, then necessarily informs the human, and
	6	allows the human a restricted time to veto before automatic execution, or
	5	executes the suggestion if the human approves, or
	4	suggests one alternative
	3	narrows the selection down to a few, or
	2	The computer offers a complete set of decision/ action alternatives, or
LOW	1	The computer offers no assistance: human must make all decisions and actions.

6.6.1.2 Levels of Automation Specific to UMVs

These general taxonomies of automation have served well for research and manufacturing systems. The unique nature of UMVs, though, has led to new characterizations of levels of automation and the relationship between the operator and the UMV. No universally agreed upon description of levels of automation has emerged, but key concepts are similar in different taxonomies. Two examples are provided below. The U.S. Office of the Secretary of Defence [5] developed a UAV roadmap and included the following levels of automation, with a proposed timeline (Figure 6-29). Note that an exponential increase in the levels of automation is predicted. In 1995, automation was at level 2, Real Time Health/Diagnosis, progressing to level 4, Onboard Route Re-planning by 2005. However, by 2015, it is predicted that automation will reach level 10, Fully Autonomous Swarms. This will require great leaps of technology and perhaps greater leaps of our understanding of how humans interact and control autonomous systems.

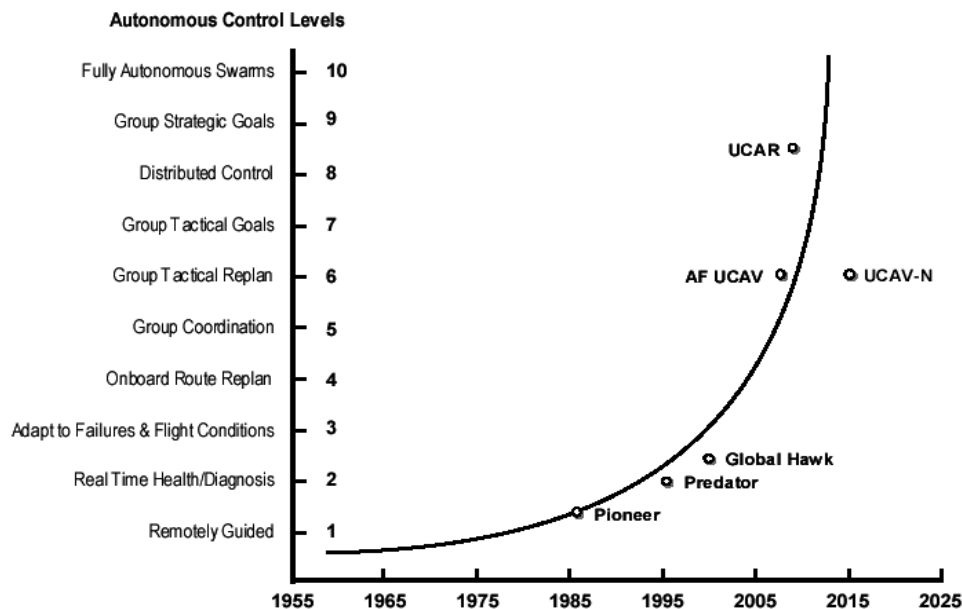


Figure 6-29: Levels of Automation [5].

Another conceptualisation of levels of automation comes from the U.S. Army Science Board [6] (Figure 6-30).



Figure 6-30: Levels of Automation, U.S. Army Science Board [6].

While less specific about time frame, the rapid increase in automation is also evident in the Army Science Board taxonomy.

In addition to the various levels of autonomy taxonomies, a distinction needs to be made concerning the levels of interoperability and control. These levels were defined in a recent NATO Standardisation Agreement or STANAG [7], as outlined in Table 6-3.

Table 6-3: Levels of Interoperability

Level I	Indirect receipt of imagery and/or data.
Level II	Direct receipt of imagery and/or data; where direct covers of reception of the UAV payload data by the UCS when it has direct line-of-sight with the UAV or a relay device which has direct line-of-sight with the UAV.
Level III	Control and monitoring of the UAV payload in addition to direct receipt of imagery/data.
Level IV	Control and monitoring of the UAV, less launch and recovery.
Level V	Control and monitoring of the UAV (Level IV), plus launch and recovery functions.

A common feature in the levels of automation taxonomies is that the level of autonomy is predicted to rise dramatically over the next several years. This rise in autonomy will dramatically affect the relationship of the operator to the aircraft. An interface designer needs to carefully examine the required or optimal levels of autonomy and the levels of control. The rest of this chapter addresses the implications of this rising automation level.

6.6.1.3 Automation: A Double-Edged Sword

6.6.1.3.1 *Potential Benefits of Automation*

Why do we automate? There are several benefits, both real and perceived. However, there are also costs (or potential costs) to automation and this section will address these costs and benefits.

6.6.1.3.1.1 Mission Capability

A commonly cited benefit of using UMVs is that they can do the jobs that humans are either reluctant to do or cannot do. These missions have been referred to as “dirty, dangerous, and dull”. UMVs can clean up toxic spills, or otherwise dirty environments without exposing human operators to this potential danger. UMVs might have saved lives at Chernobyl. About 200,000 people (“liquidators”) from all over the USSR were involved in the recovery and clean up of this accident during 1986 and 1987. They received high doses of radiation, around 100 millisieverts. Some 20,000 of them received about 250 mSv and a few received 500 mSv. Later, the number of liquidators swelled to over 600,000, but most of these received only low radiation doses [8]. UMVs might have saved lives by performing this “dirty” mission. UMVs can also operate in combat environments without exposing the operators to danger. Some visions of the future suggest that manned war as we know it won’t exist in the future. We will instead, see battles of drone aircraft and land vehicles. Automated vehicles are also very useful for performing the very dull, boring missions. These might include long duration surveillance or long egress segments. UAVs are making strides in development of this type of capability. Within two years, solar-electric airplanes incorporating energy storage for night-time operations will be capable of continuous flight for up to six months at a time at altitudes over 60,000 feet. Applications for such aircraft include telecommunications, remote sensing and atmospheric measurement.

6.6.1.3.1.2 Affordability

A major driver in automation is the perception that automated systems are less expensive to build and operate than manned systems. This is especially true in the case of small UMVs. Small UAVs such as the Raven and Pointer can be fielded inexpensively with non-pilot personnel trained to operate them, further reducing the

operational costs. Since the initial cost is low, these assets can be considered attritable. That is, loss of the asset does not result in catastrophic mission failure. This capability can, in turn, lead to a greater degree of mission flexibility, another advantage of UUVs, as mentioned above.

Operating costs are also often cited as an advantage of UAVs. This reduction in logistic footprint is realized since there is no need for pilots and supporting equipment. For example, 24 hour surveillance can be maintained by a single U.S. Army tactical UAV Shadow system, which includes 3 aircraft. This system has a logistics footprint of about 16 soldiers [9]. A similar capability from a manned aircraft system would require a much larger complement.

6.6.1.3.1.3 Workload

Automation is often implemented to reduce operator workload. There have been some very important examples of this such as the crew reduction from three to two in commercial aircraft. The 1970s saw an increase in automation which reduced workload enough on commercial flight decks to lead to this crew reduction. However, it has also been shown that automation often changes the nature of workload. The automated cockpit, for example, changes workload from physical to cognitive. For an already busy operator, that shift can dramatically increase their overall workload. Attempts to lower workload through automation need to be carefully evaluated and empirically demonstrated.

There are many important benefits of automation as discussed above, however designers must take great care not to gain through automation in one area only to detract from another area. If not properly addressed, the “costs” of automation can be greater than the reward. Some potential costs of automation are discussed below.

6.6.1.3.2 *Potential Costs of Automation*

6.6.1.3.2.1 Mode Awareness

A major concern regarding human-automation interaction has to do with mode awareness. Too many examples are available that show crews taking an action that would be correct in one mode, but that leads to problems in the present mode [10]. Consider the tragic example of Korean Airlines 007. This flight from Anchorage, Alaska to Seoul, South Korea ended in a tragedy that was a confluence of many factors, but the initiating cause was mode awareness. The pilots were in heading hold mode which keeps the aircraft on the generally correct heading within 15 degrees. This is adequate for short distances, but as will be seen the error grows dangerously large over longer flights. The pilots switched the mode control panel from heading hold to the more accurate inertial navigation system (INS). However, entry into INS mode requires satisfaction of two conditions. The aircraft needs to be within 7.5 miles of the route and pointed in the general direction of the route. One of these conditions was not met. The aircraft, therefore, never entered INS mode. Over thousands of miles, the aircraft drifted 200 miles off course into airspace controlled by the USSR and the event ended with disastrous consequences. The initial cause of this accident was the pilots’ misunderstanding of the control modes. Clearer enunciation and more intuitive control of the modes are essential to making the automation more useable and error tolerant.

6.6.1.3.2.2 Out of the Loop

In a highly automated system, the operator may be asked to monitor a number of processes. If the automation controlling these processes is largely successful and failure rates are low, the operator may not need to monitor very closely. This can lead to the operator being out of the loop when a failure does occur.

Recognizing that a failure has occurred and getting back the situation awareness needed for diagnosis can take a critically long time. This concern is especially prevalent for “semi-autonomous” systems, in which the system is highly automated without a human in the loop, until something goes wrong. The role of the human is then to quickly assess the situation and take corrective action, but having been out of the loop, this task is much more difficult. Lee and Moray called this “Out Of The Loop Un-Familiarity” [11].

6.6.1.3.2.3 Knowledge of Automation State

Highly related to being out of the loop is knowledge of automation state. In order for the operator to team with the automation, he/she needs to know what the automation is doing and why. The automation needs to be transparent and not a “black box.” The lack of this knowledge will lead to mode awareness problems, under utilization, high workload in trying to determine what the automation is doing and poor situation awareness.

6.6.1.3.2.4 Over Reliance

Automation bias can come in two forms, over reliance on automation and under reliance. Over reliance, also called complacency, takes place when operators trust the automation to the extent that they no longer cross check what it is doing, and blindly accept its direction. An example of complacency was discussed by Azar [12]. A Panamanian cruise ship, Royal Majesty, was off the coast of Nantucket. The ship was being controlled by a satellite navigation system, which failed. Several other sources of navigation information were correct and available to the crew. These however, went unmonitored and as a result the ship ran aground.

6.6.1.3.2.5 Under Reliance

Automation can also be biased toward under reliance. High false alarm rates in the early design of the Ground Proximity Warning System (GPWS) led pilots to disable the system and turn off the automation. This has also been called automation disuse by Parasuraman and Riley [13].

6.6.1.3.2.6 Brittle Automation

Automation is brittle when it works only in specific situations and doesn’t generalize well to unanticipated situations. This occurs when the models of the world instantiated in the automation are incomplete or inaccurate. This can cause users to lose confidence in the automation and not use it in situations where it may work well [14]. In these cases, it’s important to provide a cooperative aid, rather than a fully automated decision or solution. In this way, the operator can provide the flexibility needed.

6.6.1.3.2.7 Accountability

An interesting aspect of higher levels of automation is that it is less and less clear who is accountable for an erroneous action. In a manned system the pilot or driver is in control and accountable for the actions of the vehicle. However, especially under higher levels of automation, it is not clear that the UMV operators are making the decisions that account for actions of the vehicle. While this operator is still legally responsible, he may be accepting decisions made by the automation. The decision logic may have been designed by the person who developed the automation algorithms or the software engineer that produced the code. This question becomes far less academic when UVMs become armed vehicles.

6.6.1.4 Philosophies and Methodologies

6.6.1.4.1 *Human-Centered Automation*

The introduction of glass cockpits and subsequently automation to piloted fixed wing commercial aircraft led several researchers to examine the transition to automated cockpits and the human automation interaction. Wiener and Curry [15] studied the transition from traditional steam gauge cockpits to glass cockpits. This study documented problems encountered during initial transition to automation. A major issue noted by Wiener [16] is that while automation may reduce small errors, it may invite large blunders, such as the American Airlines accident in 1996 [21]. Wiener (1989) [17] found that the present generation of automation was essentially sound, but lacking in proper user interface design.

Billings [18] synthesized much of the extant work on human automation. Billings defines human-centered automation as automation designed to work cooperatively with human operators in the pursuit of stated objectives. Building on previous work, Billings developed guidelines for human-centered automation, shown in Table 6-4.

Table 6-4: Human-Centered Automation Guidelines [18]

- | |
|--|
| <ul style="list-style-type: none">• The human operator must be in command.• To command effectively, the human operator must be involved.• To be involved, the human operator must be informed.• The human operator must be able to monitor the automated systems.• Automated systems must be predictable.• The automated systems must also be able to monitor the human operator.• Each element of the system must have knowledge of the others' intent.• Functions should be automated only if there is a good reason for doing so.• Automation should be designed to be simple to train, to learn, and to operate. |
|--|

As can be seen from earlier examples, many of these guidelines have been violated in interface designs that led to predictable results. Guidelines can be useful in developing an underlying philosophy of design. Following them to specifically design an interface, however can be very difficult. Other approaches have emerged to address human-automation interaction.

6.6.1.4.2 *Intelligent Entities/Delegation*

Another way to view the interaction with UMs characterizes them as intelligent entities and seeks to delegate authority to UMs in a systematic way. The playbook approach [19] uses the sports analogy that the operator is the coach and can call a "play." The intelligent entities know what their roles and responsibilities are within that play and can execute those autonomously. For example, an operator may need to get information about a particular intersection of two roads. He/she would call the "recon a point" play. The UM asset or assets know what this means, a) move into a clandestine position, b) observe the intersection for a specified amount of time and c) return the sensor information to the operator. These plays can be modified by the operator as he/she sees fit.

6.6.1.4.3 UMs in a Network Centric System

Yet another way to view UMs is as information sources. A commander may have a network of UMs at his or her disposal. Instead of specifically commanding any asset, he/she would instead ask the network for information. For example, if the commander needs information about enemy assets in a certain area, he can ask the network for that information. The network knows what assets are available, and which are needed for this request. Based on the priority of the request, the network assigns assets to obtain the requested information and forward it back to the requesting commander. In this network centric application, the UMs are efficiently utilized and available to a wider tactical community.

These approaches are not mutually exclusive and indeed may work well together. Further, additional ways to look at automation have also been suggested: automation as an associate [20], UMs working as a team or swarming, and automation serving as an electronic crew-member or wingman. The task of the interface designer is to determine how these may be adapted to best serve the operator's needs. They may serve as a toolkit for human-automation interface design.

6.6.1.5 Interface Implications of Automation

This section summarizes some of the more salient points of the preceding discussions and draws on other sources to provide issues to consider in UMV interface design. They are not meant to be exhaustive guidelines or a checklist, but rather things to look out for and consider.

- 1) Automation does not reduce operator workload per se; it may change the nature of the workload or may even increase it. Automating the "stick and rudder" flying of a UAV or "hand control" of a UMV to way point control reduces the continuous in the loop manual workload. However, the operator is now a supervisor of this automated system and has to monitor the vehicle state and the automation controlling the vehicle. The cognitive workload associated with this supervisory control may well be higher than the workload of physical control.
- 2) It is critical for appropriate use of automation that the user understand how the automation works and what mode the automation is in. Without this understanding, automation bias can result.
- 3) There is an inexorable trade off between higher levels of automation and unpredictability. As systems move more and more toward automation, they are, by definition, less predictable and therefore don't allow predictability or insight into what the UMV is doing (see # 2).
- 4) All automation is not created equal. It can be brittle, unpredictable, and prone to bias. Knowing about these pitfalls is half the battle. A designer must carefully look at where and how the automation may fail. Is the mission at a critical point? Does the automation gracefully degrade? Does the operator know the automation is failing?
- 5) In UMV operation, there are two tasks: vehicle control and sensor control/interpretation, however, they are often treated as one. An earlier section discussed levels of automation, the first taxonomy is almost entirely in terms of vehicle control. The second taxonomy from the Army Science board addresses a bit more mission oriented tasks, but is none the less a unitary scale. It's quite likely that the sensor interpretation task is the more difficult of the two tasks, and the more difficult to automate. As programmatic goals move toward control of multiple UAVs and even swarms, it's important to ask who is interpreting the sensor information and/or if that task is automated.
- 6) Beware of systems described as "semi-autonomous." Many current systems are designed such that a person is the ultimate monitor and failsafe, but if automation levels are high, the operator is prone to being out of the loop (see above). It is dangerous to design systems that require humans to manage

contingencies when the automation fails. However, it should be noted that some excellent work has been done in this area under names of shared control, traded control and situation adaptive autonomy. The reader is encouraged to fully explore these areas when faced with “semi-autonomous” systems.

- 7) UMs are tools to provide information. It should be remembered that UMs are just one more way to provide information to commanders and decision makers. As such, it is important to focus on the information coming in and the information presentation.
- 8) Lessons learned from manned aircraft automation and other domains such as power plants offer invaluable lessons to draw from. Years of automation errors and poor implementations provide rich information sources.
- 9) Individual differences in the use of automation make predictions difficult (Parasurman and Riley [13]). It is important for the user to know the rationale and pay-offs for using the automation.

There is no formula for interfaces with automation. There are guidelines as have been discussed, but most importantly the designer needs to be aware of these issues, communicate to the user and continually evaluate the system.

6.6.1.6 Research Issues

In many respects, work with UMs and human-automation interfaces is in its infancy and many research questions remain. A great deal of research is called for to help answer these questions. In the area of automation, here are a few key research areas. These research areas are also addressed in Chapter 7 of this volume.

6.6.1.6.1 *Level of Automation*

An early section discusses the various levels of automation and levels of control. However, it's not clear which of these or what combination of these are optimal. Should a designer always try for the highest level of automation that is possible? Increasing levels of automation will lead to more mission capabilities, but at what cost? How will the operator manage off-nominal events?

6.6.1.6.2 *Level of Involvement*

How can a designer increase levels of automation, but keep the operator informed and in control? Should the designer keep the automation level lower to keep the operator in the loop? Or could they build highly automated systems, but build in tasks that keep the operators' situation awareness high? What interfaces facilitate this?

6.6.1.6.3 *Automation Transparency*

How can automation interfaces be designed so that the actions and intentions of system are clear to the operator? Pilots often struggle with understanding what the flight management system is “trying to do.” This needs to be avoided. The intent of the automation needs to be clear to the operator in control. How this can be done, to what extent it is necessary, and what interfaces facilitate this are major research questions.

6.6.1.6.4 *Training*

The question of operator qualifications have become very important, especially when in control of UAVs. Do the operators need to be qualified pilots or can they simply be trained on the system that they are flying.

These two different schools of thought have emerged, but there is little research available addressing this issue. A clear definition of the knowledge, skills and abilities to operate UMVs is needed to help answer this question.

There also remain many issues not raised in this chapter, but that will need to be addressed by UAV designers in the near future. The U.S. Army has plans to use manned helicopter and UAVs as teams. How should an interface be designed that optimises teaming between manned assets and unmanned assets? They also have plans to control (at some level) UAVs from helicopters. What is the optimal level of automation? Of control? What are the information requirements?

A last issue that will be raised here is one of commonality, or lack thereof. Manned aircraft have developed standards over the years, the classic example being the T arrangement of the airspeed, altitude and heading in an aircraft cockpit. This has allowed pilots to move from one aircraft to another with minimum levels of negative transfer. No such standards exist for UMV control station design. This has led to vastly different designs by each manufacturer and the result that operators must be trained very specifically on each platform control station, with little or no advantage of previous learning. This lack of standard design must be addressed for UMVs to reduce training costs, logistics and operation errors.

6.6.1.7 References for Implications of Automation/Autonomy

- [1] Oxford Dictionary of Current English (1998). Oxford University Press: Oxford, New York.
- [2] Sheridan, T.B. (2002). Humans and Automation: System Design and Research Issues. John Wiley & Sons, in cooperation with HFES: Santa Monica, CA.
- [3] Sheridan, T.B. and Verplank, W.L. (1978). Human and Computer Control of Undersea Teleoperators (Man-Machine Systems Laboratory Report). Cambridge: MIT.
- [4] Parasuraman, R., Sheridan, T.B. and Wickens, C.D. (2000). A model for types and levels of human interaction with automation. IEEE Transactions on Systems, Man and Cybernetics, 30(3), 286-297.
- [5] Office of Secretary of Defense. (2005). Unmanned Aerial Vehicle Roadmap: 2005-2030. OSD: Washington, D.C.
- [6] Army Science Board. (2004). Autonomy Levels for Unmanned Systems Workshop. Huntsville, AL.
- [7] Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability (2004). STANAG 4586(2).
- [8] <http://www.aerovironment.com/area-aircraft/unmanned.html>
- [9] Dowell, S.R. (2005). Shadow Logistics Footprint, personnel communications.
- [10] Degani, A. (2003). Taming HAL: Designing interfaces beyond 2001. New York: Palgrave MacMillian.
- [11] Lee, J. and Moray, N. (1992). Trust, control strategies and allocation of function in human-machine systems. Ergonomics, 35, 1243-1270.
- [12] Azar, B. (1998). Danger of automation: It makes us complacent. APA Monitor, 29(7).
- [13] Parasuraman, R. and Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. Human Factors, 39(2).

- [14] Layton, C., Smith, P. and McCoy, E. (1994). Design of a cooperative problem solving system for enroute flight planning: An empirical evaluation. *Human Factors*, 36(1), 94-119.
- [15] Wiener, E.L. and Curry, R.E. (1980). Flight-deck automation: Promises and problems. NASA Technical Memorandum 81206. Moffett Field, CA.
- [16] Wiener, E.L. (1985). Beyond the sterile cockpit. *Human Factors*, 27, 75-90.
- [17] Wiener, E.L. (1989). Human Factors of Advanced Technology ("Glass Cockpit") Transport Aircraft. NASA Contract report NCC2-377.
- [18] Billings, C.E. (1997). *Aviation automation: The search for a human-centered approach*. Malwah, NJ: Erlbaum.
- [19] Miller, C.A., Goldman, R.P., Fubj, H.B., Wu, P. and Pate, B. (2004). A playbook approach to variable autonomy control: Application for control of multiple, heterogeneous unmanned air vehicles. American Helicopter Society 60th Annual Forum Proceedings, pp. 2146-2157, Alexandria, VA.
- [20] Miller, C.A. and Riley, V. (1994). Achieving the associate relationship: Lessons learned from 10 years of research and design. 3rd International Conference on Human-Computer Teamwork: Cambridge, U.K.
- [21] Aeronautica Civil of The Republic of Columbia (1996). Aircraft Accident Report: Controlled Flight Into Terrain, American Airlines Flight 965, Boeing 757-223, N651AA, Near Cali, Colombia, December 20 1995.

6.6.2 Control/Display Interfaces for Decision Support

Control and display interface design has always been a key concern for operator station development. However, future control stations that employ a single operator to control multiple UUVs will require controls and displays that not only enable conventional operator tasking, but also support supervisory tasks as well. These tasks include quick assessment, judgment and reaction to the appropriateness of the automation's changing plans and actions, as well as continually assessing the impact of these changes on overall mission objectives, priorities, etc. Moreover, as the number of controlled vehicles increase, it will be a challenge for the operator to maintain situation awareness through long periods of nominal operations interjected with short periods of time-sensitive contingency operations. The UUV interfaces need to effectively cue the operator's attention to critical information and support rapid task re-allocation. Thus, UUV interfaces must be tailored to increasing system autonomy and novel decision support systems.

Research is needed to support the design of situation assessment and decision support technologies that maximize flexible, fault-tolerant supervision of multiple intelligent semi-autonomous UUVs by a single operator. This technology area is more fully discussed elsewhere in this report.

Research must also specifically consider the design of tailored controls and displays for UUV decision support systems. Although often overlooked, control/display interfaces are critical to obtaining maximum benefit from a decision support system. If the controls and displays do not support the operator's decision making process, the operator's effective interaction with the intelligent automated systems will be compromised and the benefits of the automation will not be fully realized. In sum, effective decision support control/display interfaces are vital to the UUV operator's ability to make timely, accurate decisions.

This section summarizes a survey of decision support literature that sought to determine the degree to which controls and displays are considered in the design of previous decision support systems, identified key decision support interface types, and presented a notional classification system. The full survey is more fully described elsewhere [1].

6.6.2.1 Methodology for Decision Support Interface (DSI) Survey

Thirty-four DSI research papers were surveyed. The sampled literature included journal articles, conference proceedings, book chapters, and technical reports. To be included in the survey, two qualifications had to be met. First, the research had to involve a problem domain in which a human user was challenged by requirements to make quick and accurate decisions. Thus, the documentation did not need to address the UMV domain; there are a multitude of application environments that require decision support, the findings of which are potentially applicable to UMV supervisory control. Second, the research had to involve the evaluation of an interface concept – a decision support control and/or display was manipulated as an independent variable. Thus, this survey focused on empirical evaluations while steering away from papers that broadly addressed decision support issues, theory, and system design.

For each document in the survey, notes were made in multiple columns of a table [1]. Besides bibliographic information, there were seven columns to capture information on the nature of the decision support interface used in the research and the results of the evaluation. The following further describes the content noted in each column:

- DSI Category: the general grouping of the decision support interface (DSI) concept (e.g., attentional cue, status display, etc.).
- DSI Description: the purpose or intended benefits of the decision support concept.
- Intelligent?: the computational functionality of the DSI as to whether it is based on artificial intelligence algorithms, knowledge-based systems, modeling efforts, or simple rule-based logic.
- DSI Control Concepts: identifies any control concept used to interface to the decision support.
- DSI Display Concepts: describes the content/format of information presented in a DSI.
- Short Summary: an overview of the experimental design, independent variables and user tasks.
- Lessons Learned: summarizes results found with the particular decision support interface.
- Conclusions: lists DSI findings that may be generalizable to other decision support systems.

6.6.2.2 Decision Support Interfaces: Classification

Entries in the table were examined to derive major groupings. First, overall grouping of the decision support interfaces into ‘controls’ and ‘displays’ was accomplished. Next, further classification was accomplished based on other factors, such as the degree of computational functionality (intelligence) in implementing the interface and the nature of the support it afforded.

6.6.2.2.1 Decision Support Controls

Controls were first classified by control type (conventional, non-conventional). The majority of controls employed in the decision support interface literature sampled were conventional input devices – mouse and keyboard. Less often, researchers evaluated decision support control with novel devices. These included voice recognition, touch-screens, and reduced keyboards [2], and a haptic stick [3]. Within each control type, controls were grouped by technology type.

It was also deemed useful to classify by the method used to achieve control. For instance, researchers make the distinction between controls that are ‘bottom-up’ as opposed to ‘top-down’ [4]. In bottom-up control, individual elements of the decision problem are specified in detail, and the user then receives updates on each element. In top-down control, an overview of the decision problem is formulated, each element of the problem is then refined, and the user is guided down through the hierarchy of information. Another sub-classification is whether the control employed intelligent filters that retrieve, fuse, and manage information during the control process [3]. In contrast to having intelligent filters, the design can be based on the user changing system constraints, parameters, and/or plans which results in the initialization of processes that change (i.e., control) system states [2]. Two opposing control methods make up a final defined control category: closed loop control versus open loop control. With open-loop control, no feedback is sent back to the controller because the control equation is well-accepted. During closed-loop control, feedback is provided to the controller so that any subsequent input brings the system closer to the goal state.

6.6.2.2.2 *Decision Support Displays*

The sampled decision support interface literature described many types of displays. These were grouped into two major categories: displays that are simply rule-based and ones that are knowledge-based.

Automated warnings, alerts, and cues consisting of simple notifications (visual, aural, tactile) when a rule or goal state is broken (or met) constituted one common type of rule-based decision support interface display. These displays can be multi-modal. Attention cuing displays aid target prosecution and highlight critical information or points of interest through displays technologies such as synthetic vision symbology overlaid conformal on a camera video display, automatic target cueing, and assisted target recognition [5,6,7]. Status displays also mainly use a rule-base to present the decision maker with key parameters and their associated values. These displays can provide system history in the form of graphs, intelligence reports, or logs. Similarly, status displays can offer classification, filtering, or generalizing of situations and systems [8,9]. Action recommendation displays take status display information and use another rule-base to recommend a course of action to the decision maker (e.g., options, strategies), but does not implement the action [10,11]. A specific example is a Highway-in-the-Sky display that provides flight guidance [12]. Adaptive/adaptable systems are another type of rule-based display. Adaptable systems allow the operator to initiate automated state and mode changes, while adaptive systems allow the operator or automation to initiate the changes depending on the automation management schema. In some designs, a simple rule-base can cause automated mode changes when the operator crosses threshold values in path deviations, EEG index (workload measure based on electroencephalographic signals), or altitude (such as a ground collision avoidance system). Rules could also trigger the system automation to collect, filter, organize, and present information to the operator in anticipation of upcoming decisions.

Knowledge-based decision support displays are also referred to as intelligent displays. Definitions of “intelligence” vary, but many include the ability of an entity to achieve goals in complex real world situations. Some definitions specify that the entity must perceive, learn, reason, communicate, and act [13]. Using intelligent systems to support decision making is most appropriate for well-structured, clearly defined decision situations. Many types of intelligent displays rely on intelligent agents that work in the background to collect, filter, organize, and present information to the decision maker. With an intelligent system, status displays can also provide a feed-forward presentation to support the decision maker in anticipating future system states through Gantt charts and other predictive displays. Intelligent agents can also expand the capabilities of displays in adaptive systems. Other types of knowledge-based decision support displays are plan generators and evaluators. With these displays, operators can a) generate a plan and then have the system evaluate (critique) it; b) tweak a system-generated plan and then have it evaluated; or c) use the intelligent

technology to predict future system states by inputting “what if?” scenarios. The generation and evaluation of these plans are usually dependent on optimization algorithms or knowledge-based expert system modeling. Similarly, intelligent adaptive decision support displays rely on intelligent agents to monitor situations and decide what information to present to the user, in what format, and at what time. Some intelligent agents may replace some of the operators in a team decision making environment. To make effective team decisions, the agent-user collaboration, negotiation, and dialogue must work successfully so the agent can provide aggregate, inferential, and decision information to the operator(s) without information overload.

6.6.2.3 Decision Support Interface Survey: Lessons Learned

6.6.2.3.1 General Findings

One objective of the survey was to determine the degree to which controls and displays are considered in the design of decision support systems. For the literature sampled, the majority dealt with display interfaces as opposed to control interfaces. This finding is not surprising and can be viewed as reflecting the larger body of research dealing with displays, compared to controls, in overall human factors literature.

Another finding raises a more pressing concern. First, note that all the sampled literature focused on evaluating a control and/or display interface for a decision support system. However, less than a third explained the rationale for the control/display concept chosen to be employed with the particular decision support system. In other words, these reports didn’t cite published research or a previous application of the control/display that supported its utility in the decision support system featured in the report. Although this finding may only reflect incomplete documentation by the authors, it is feared that it is indicative of an inadequate prioritization on control/display design. Another possibility is that there are problems inherent in generalizing existing control/display findings to decision support systems. Regardless, this finding supports the need for additional research on how best to apply control/display interfaces for use with decision support systems for UMV operators.

Below is a summary of survey findings. Complete results can be found in [1].

6.6.2.3.2 Decision Support Controls

The literature survey indicated that the use of non-conventional controls, such as speech recognition, touch-screens, and reduced (custom function) keyboards generally improved operator performance and either reduced or had no negative effect on perceived workload [2]. Another finding was that in many decision support systems, there are alternate control methods simultaneously available to the operator. For instance, the decision support system may allow the operator to choose:

- Information search/acquisition method, such as bottom-up (start with detailed query and get updates/notifications) or top-down (global perspective with guides to detailed information);
- Information assessment method (what filters or constraints are employed);
- Whether to view recommended alternatives or only the “optimal” solution;
- Control input device (by sketching, typing, or speaking novel problem solution into the system).

Empirical results suggest that these control choices could significantly affect the decision support effectiveness and overall mission performance. For instance, choosing to select a path recommended by the decision support system, as opposed to using a more cumbersome sketch/graphical input method, can bias the operator’s decision [9].

6.6.2.3.3 *Decision Support Displays*

6.6.2.3.3.1 Rule-Based Displays

Automated Warnings, Alerts, and Cues

Similar to decision support controls, performance with non-conventional decision support displays was generally better than with conventional visual displays. Multi-modal displays were found to improve performance for many tasks, especially when used as a redundant cue to visual information. Examples include haptic [3], auditory [14], and voice displays/feedback [2,15]. Another key finding related to cuing displays is the potential for cognitive tunneling. Cognitive tunneling can occur when the operator becomes focused on the cue being displayed to such an extent that other important objects in the view are not attended [16]. Research is needed to explore how cue displays might be designed to minimize the negative effects of cognitive tunneling. Decision support cues can also unintentionally obscure both expected and unexpected information [7]. Techniques are being explored to minimize this problem [17]. Finally, there is a possibility that operators will over rely on cues displayed from the decision support system, resulting in operator complacency [15].

Status and Action Recommendation Displays

In general, the sampled research showed that status and action recommendation type decision support displays were beneficial to operators' performance in the task environments tested. However, the reliability of information displayed begins to have a more consequential impact with recommendation displays. This is because it is more difficult for operators to judge from a recommendation display that underlying data is suspect. Studies have shown that when the decision support system has reduced reliability, operator performance is better with a status display by itself [10,18]. Additional findings suggest displays that incorporate graphics are better than text-based displays. It was hypothesized that the graphic displays were rated higher in usability because they support human pattern recognition or recognition-primed decision-making [8].

6.6.2.3.3.2 Knowledge-Based (Intelligent) Support

Since knowledge-based displays are more difficult and time-consuming to develop and require a well-defined domain, empirical testing is scarce and this was reflected in finding only a few relevant documents in the literature sampled. One evaluation of an advisory tool designed to generate flight paths around weather showed that providing a display to aid operators to manually develop their own plan prior to getting a plan from intelligent agents enabled operators to catch faulty plans better compared to displays that only provided an auto-generated plan [19]. This result suggests that a cooperative process between the operator and the decision support system would help minimize the occurrence of automation bias.

The nature of the cooperative process can also impact the effectiveness of the decision support system. One study [20] demonstrated that operators could generate plans for distribution to team members faster with an intelligent planner that provided displays to assist the operator through the planning process (providing suggestions, blanks to fill, etc.), than with an intelligent planner that critiqued an operator-generated plan (displaying how good it was according to critical mission measures). This illustrates how display design needs to simultaneously take into account control design as well. In other words, the optimal nature of the operator-system dialogue for capitalizing on the benefits of the decision support system needs to first be determined and then supported by the control/display interface.

Information reliability also plays a role in the effectiveness of decision support system displays. In the study mentioned above [20], a display with no support was compared to three different types of decision support

displays: one that just listed raw data, one with the data classified into columns, and one in which accuracy probability information was also provided. By manipulating the source of errors (raw data, erroneous classification, erroneous probability), the results suggest that presenting the data classified into columns was best, despite the fact that subjective ratings indicated that operators trusted all three types of displays equally. Also, the finding that operators' trust was the same for all display types illustrates the value of presenting key information in the display by which the operator can judge the adequacy of the data and, ultimately, improve the decision making process.

As an example of a promising knowledge-based decision support display, consider [21]. These researchers developed a tactical display concept consisting of a set of PCE (Predicted-Capability-Envelope) contours overlaid on a 2D map representation (Figure 6-31). These PCE contours describe the maneuvering margins of ownship movements, in relation to other moving platforms' motions and ownship capabilities. Capability prediction is a model-based concept that takes dependencies between control actions and effectiveness parameters into account. This involves calculation and presentation on a navigation display of the total maneuvering margins, the so-called PCE. The concept was developed for a ship-maneuvering environment. In this case, the predicted margins include restrictions due to boundaries and other traffic ships. The PCE represents the complete reach of the controlled vessel for a particular time horizon. By intersecting the PCE with a required minimum safety distance, an integral representation of (other traffic) threats and (controlled ship) capabilities is obtained. Provided that course and speed of other ships remain the same, the presented threats will be geographically stable areas. Navigators may consider these threats as obstacles in the fairway. Thus, an integrated navigation display is obtained which provides an overview of the ship's maneuvering and collision avoidance information for a particular navigation task. With respect to the PCE concept, several in-depth part-task simulator studies were performed to quantify the effects of using PCE on navigator performance. The experimental results show that capability prediction is far more effective than other prediction information, e.g., path prediction [22].

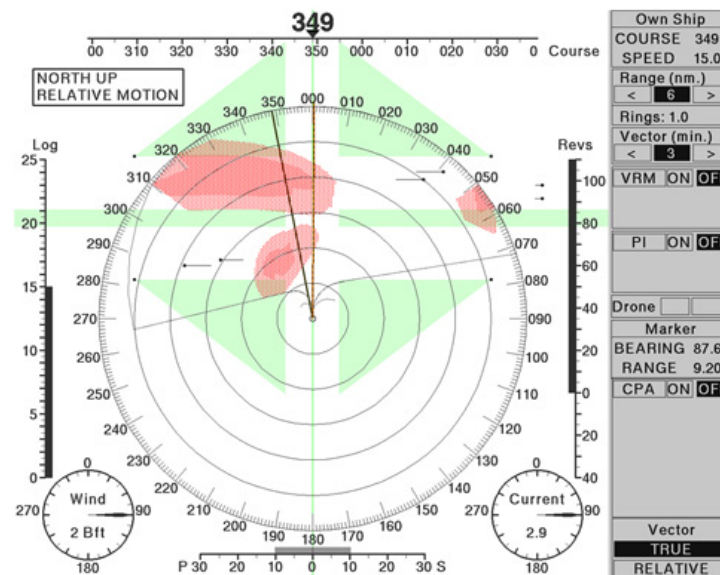


Figure 6-31: PCE Display Representation as an Overlay on a Radar Display. The center dot represents ownship position. Starting at this position, an area is marked (thin grey envelope) for which proximity information is calculated. The red zones represent areas in which the own ship will be within one mile passing distance from another vessel.

6.6.2.4 Survey Implications on UMV Supervisory Control

Decision support interfaces are key to realizing the benefits of intelligent automated systems that facilitate single operator control of multiple UUVs. If the interface fails to support the operator's decision making process, the operator's ability to make timely, accurate decisions will be compromised as will the ability to judge the operation of the semi-autonomous systems. This literature survey, however, suggests that attention to date has focused on development of the knowledge-base for the decision support rather than the optimal design of the controls and displays used with the decision support system. Thus, there is a need for research that systematically addresses interface issues for various categories of UUV decision support systems.

Some directions for this research are indicated in the surveyed literature. For instance, research on multi-modal interfaces (e.g., speech-based input and visual/aural redundant displays) supports their use with decision support systems. The interaction of control and display design was also illustrated, showing that the desired operator/system dialogue or collaboration must also drive interface design. Other studies demonstrated the value of presenting key information in the display by which the operator can judge the adequacy of the data and, ultimately, improve the decision making process. For UUVs, this would suggest displaying status information for each UUV under supervision, increasing the displayed information by a factor of the number of vehicles. To minimize information overload/retrieval problems, an intelligent system which highlights important information while maintaining the availability of other information may be useful, as well as innovative display approaches that support anticipatory decision-making.

In research evaluating candidate UUV controls and displays, the reliability, bandwidth, and timeliness of information need to be manipulated to determine their effect on the utility of the decision support interface. It is also important that the interface design/evaluation takes into account issues of cognitive tunneling, effective information retrieval, and automation bias. Workload and vigilance demands are also critical.

6.6.2.5 References for Decision Support Control/Display Interfaces

- [1] Calhoun, G., Ruff, H., Nelson, J. and Draper, M. (2005). Survey of decision support control/display concepts: classification, lessons learned, and application to unmanned aerial vehicle supervisory control, Proceedings of the 11th International Conference on Human Computer Interaction, Las Vegas, CD-ROM.
- [2] Winter, H., Champigneux, G., Reising, J. and Strohal, M. (1997). Intelligent decision aids for human operators. AGARD Symposium on Future Aerospace Technology in the Service of the Alliance, AGARD-CP-600, Vol. 2, Palaiseau, France, 14-17 April.
- [3] Scerbo, M.W. (2000). Adaptable and adaptive technology in the lab and in the field. Proceedings of the Human Performance and Situation Awareness in Automation Conference, pp. 57-62.
- [4] Sycara, K. and Lewis, M. (2002). From data to actionable knowledge and decision. Proceedings of the Fifth International Conference on Information Fusion, Annapolis, MD, July 7-11.
- [5] Endsley, M.R. and Kaber, D.B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics*, 42(3), 462-492.
- [6] Hughes, S. and Lewis, M. (2002a). Attentive interaction techniques for searching virtual environments. Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society, Baltimore, MD., pp. 2159-2163.

- [7] Hughes, S. and Lewis, M. (2002b). Directing attention to open scenes. Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society, Baltimore, MD., pp. 1609-1612.
- [8] Morrison, J.G., Kelly, J.T., Moore, R.A. and Hutchins, S.G. (1998). Implications of decision making research for decision support and displays. In: J.A. Cannon-Bowers and E. Salas (Eds.), Making decisions under stress: Implications for individual and team training. Washington, DC: APA Press, pp. 375-408.
- [9] Smith, P.J., McCoy, C.E. and Layton, C. (1997). Brittleness in the design of cooperative problem-solving systems: The effects on user performance. IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans, (27) 3, May, pp. 360-371.
- [10] Crocoll, W.M. and Coury, B.G. (1990). Status or recommendation: Selecting the type of information for decision aiding. Proceedings of the Human Factors Society 34th Annual Meeting, pp. 1524-1528.
- [11] Woods, D.D. (1986). Paradigms for intelligent decision support. In: Holnagel, M., and Woods, D. (Eds.). Intelligent Decision Support in Process Environments. New York: Springer-Verlag, 153-173.
- [12] Snow, M.P. and Reising, J.M. (1999). Effect of pathway-in-the-sky and synthetic terrain imagery on situation awareness in a simulated low-level ingress scenario. Proceedings 4th Annual Symposium on Situational Awareness in the Tactical Air Environment, Piney Point, pp. 198-207.
- [13] McCarthy, J. (2003). What is artificial intelligence? Stanford University, web essay, from <http://www-formal.stanford.edu/jmc/whatisai/whatisai.html>
- [14] Olson, W.A. and Sarter, N.B. (2001). Management by consent in human-machine systems: When and why it breaks down. Human Factors, (43)2, pp. 255-266.
- [15] Foy, L. and McGuinness, B. (2000). Implications of cockpit automation for crew situational awareness. Proceedings of the Human Performance and Situation Awareness in Automation Conference, pp. 101-106.
- [16] Yeh, M. and Wickens, C.D. (2001). Display signaling in augmented reality: Effects of cue reliability and image realism on attention allocation and trust calibration. Human Factors, 43(3), 355-365.
- [17] St. John, M., Maines, D.I., Smallman, H.S., Feher, B.A. and Morrison, J.G. (2004). Heuristic automation for decluttering tactical displays. Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting, HFES: Santa Monica, CA, pp. 416-420.
- [18] Cummings, M.L. and Guerlain, S. (2005, in review). The decision ladder as an automation planning tool. Cognition, Technology, and Work, Springer-Verlag London Ltd.
- [19] Guerlain, S. (2000). Interactive advisory systems. Proceedings of the Human Performance and Situation Awareness in Automation Conference, pp. 166-171.
- [20] Lewis, M. (1999). Anticipation delegation, and demonstration: Why talking to agents is hard, In: M. Klusch, O.M. Shehory, and G. Weiss (Eds.), Cooperative Information Agents III, Lecture Notes in Computer Science, Vol. 1652, Springer-Verlag Berlin, Heidelberg, pp. 365-389.

- [21] van Breda, L. and Passenier, P.O. (1998). The effect of path prediction on navigational performance. *The Journal of Navigation*, 2, 216 228. Cambridge, UK: Royal Institute of Navigation.
- [22] van Breda, L. (1999). Anticipating behaviour in supervisory vehicle control. PhD thesis. Delft, The Netherlands: Delft University Press.

6.7 ADDITIONAL CONSIDERATIONS FOR UMV INTERFACES

The environment and methods in which a UMV is intended to operate will dictate particular UMV's control station affordances and constraints. This section examines the scale and variability of control stations for UMVs, identifying primary affordances and unique constraints associated with each. This section also discusses issues associated with controlling UMVs from moving platforms.

6.7.1 Scale of UMV Operator Interface

Scale, in this context, is used to describe the constraints imposed upon the design of UMV control stations. The scale ranges from man portable to large space platforms and all are limited to single operator control.

6.7.1.1 Man-Portable Platforms

In man portable platforms, the UMV is ideally very small, lightweight, rugged, and easy to operate [1]. It is essential that this platform meet these characteristics because a typical operator will be transporting the entire UMV system along with other mission critical equipment. These UMVs are usually used for “what’s over the hill” type missions; requiring fairly autonomous operation to gain time critical, nearby information. The control stations for man portable UMVs will typically be no larger than a laptop and can be made to fit on smaller devices such as a PDA or head-mounted displays. For example, the Pointer UAV, developed by AeroVironment Corporation, is operated by the user through a large tablet-like PDA [2] (Figure 6-32). Another example of this can be seen in [3]. However, ruggedization of this equipment will generally increase weight and size.



Figure 6-32: Example of Man-Portable Control Station. (Source: <http://www.aerovironment.com/>).

6.7.1.1.1 *Affordances Provided by Man-Portable Platforms*

Of the three main classes of UMV control stations, man portable stations afford the fewest resources for interfacing with the vehicle. Often times man portable UMVs require direct line-of-sight control of the vehicle. This allows more immediate responses to control inputs. The short duration of operations and lack of control station equipment should minimize the amount of ergonomic concerns with respect to body posture, workstation design, etc. Decreased available interface real estate requires simplified control inputs into the UMV system, and varied operating environments may allow for more unconventional input methods into the system such as speech recognition.

6.7.1.1.2 *Constraints Associated with Man-Portable Platforms*

Interface designs must be optimized for essential basic functions, leaving little room for displays and controls that may expand capability. Further, the operating environment of a man portable UMV control station can vary more than restricted space and unlimited space platforms, increasing the need to make robust, hardy equipment. Control input devices cannot be overly sensitive or delicate (e.g., a PDA-style stylus may be too fragile of an input device if the operating environment requires all weather operations). Display screens must be able to be viewed under less-than-ideal conditions (e.g., bright desert environments), and access to Command and Control (C2) information for these systems is limited. Operators must act as the vehicle director and perform multiple other functions that need to be executed, requiring a large amount of autonomy on the vehicle's part. Man portable UMV platforms create many challenges if an operator needs to operate more than one vehicle at a time.

6.7.1.2 **Restricted-Space Platforms**

Restricted space control stations are characteristically built to be semi-mobile, often in a portable trailer. However, restricted-space platforms may also be in the back of another vehicle, such as a High-Mobility Multi-purpose Wheeled Vehicle (HMMWV) or tight quarters on a ship. Space is often limited, varying based on the UMV system it supports, but there is no requirement for the system to be man portable. An example of a restricted space control station can be seen in Figure 6-33.



Figure 6-33: Example of Restricted-Space Platform.

6.7.1.2.1 *Affordances Provided by Restricted-Space Platforms*

UMV restricted space control stations possess much more interface space compared to man portable systems. Additionally, the UMV control station operating environment can be managed to a large degree with respect to the station's temperature, lighting, noise, etc. This allows some degree of flexibility in the design of the displays and controls, as they do not have to be as hardy. The increased space in these stations also allows operators to have additional, but not necessarily vital tools, to improve areas such as situation awareness and workload. However, it is important to remember that display and information input space, while larger than the man portable systems, can quickly become congested. Another benefit to the restricted space control station is the greatly improved access to C2 information as these platforms have the potential for SATCOM communications.

6.7.1.2.2 *Constraints Associated with Restricted-Space Platforms*

As would be expected, restricted space platforms have fewer constraints than man portable stations, but more than unlimited space designs. Often, achieving a good ergonomic layout in restricted space control stations is difficult. Vehicles operating from these control stations usually demand high levels of operator oversight, requiring multiple display and control surfaces. Fitting all the controls and displays is typically the first priority; accommodating the human is secondary. Maintenance access is often restricted as is any redundancy in the controls or displays. Information input is often performed through the use of conventional mouse, keyboard, and/or joystick devices. Technologies such as speech recognition can ease the space requirements for control surfaces in these platforms and allow for more display area, better ergonomics, and increased capability tools. Human interface design needs to consider how best to access and display large amounts of information on few displays (i.e., what is an appropriate cognitive distance for each item, how much digging for information should be required – information depth versus breadth, etc.).

6.7.1.3 **Large-Space Platforms**

In a platform where space is abundant and more than able to accommodate the operators, the station would most likely be located in some sort of bunker or building [1]. These arrangements allow for the greatest degree of control with respect to the control station operating environment (e.g., temperature, lighting, noise, etc.), but the least amount of mobility. These systems might typically be large platforms with highly autonomous vehicles performing numerous functions that are all tied into net centric feeds. Some potential examples of large-space platforms can be seen in research with data walls, as shown in Figure 6-34.



Figure 6-34: Example of Large-Space Platform – A Data Wall at U.S. Air Force Research Laboratory.

6.7.1.3.1 Affordances Provided by Large-Space Platforms

Perhaps the most appealing aspect of a large space platform is that it could allow for a truly user-centered design approach as defined by [4]. While the user-centered design approach should be used for the man portable, restricted space, and large space platforms, it can more fully be exploited in the large space system. Using this approach, the system could be designed with the user in mind at all stages, maximizing the technologies that would allow an operator to function at peak efficiency and effectiveness. It is possible to incorporate all expanded capabilities as well as basic functionality. The size could be enlarged to fully accommodate proper ergonomic design, information input, and display space needs of a human operator. In the large space platform, it is possible to completely control the operator's working environment – ensuring no stray lights, sounds, or other disturbances interfere. This type of platform would be ideal for controlling multiple UMVs or any type of system that requires crews of operators.

6.7.1.3.2 Constraints Associated with Large-Space Platforms

The unlimited space design is not without constraints. The biggest drawback is its lack of mobility. To move the entire station from one area to another becomes a long and difficult task. There is also an issue of oversaturation. For instance, just because there may be space to add an additional monitor to the workstation does not mean it would improve the operator's performance. Providing an operator with additional channels of information to monitor can decrease overall situation awareness, increase workload, increase the possibility of errors due to missed information or misperceived information, increase the possibility of cognitive tunnelling, as well as a host of other problems. Human factors engineering would need to ensure the system does not inundate the user with too much information or too many controls.

6.7.1.4 References for Scale of UMV Operator Interface

- [1] U.S. Department of Defense. Unmanned Aircraft Systems Roadmap 2005. Retrieved November 30, 2005, from <http://www.acq.osd.mil/usd/Roadmap%20Final2.pdf>
- [2] AeroVironment, Inc. Pointer FQM-151A: Unmanned Aerial Vehicle (UAV) System. Retrieved November 3, 2005, from <http://www.aerovironment.com/area-aircraft/prod-serv/ptrdes.pdf>
- [3] Goodrich, M. and Quigley, M. (2004). Mini-UAV telemetry and imaging visualization for searching tasks [Abstract]. Proceedings of the Cognitive Engineering Research Institute Annual Human Factors of UAVs Workshop, 1. Retrieved December 1, 2005, from <http://www.cerici.org/workshop/abstract/Goodrich.pdf>
- [4] Norman, D.A. and Draper, S.W. (Eds.). (1986). *User centered system design*. Hillsdale, NJ: Lawrence Erlbaum Associates.

6.7.2 UMV Operation from Moving Platforms

An interesting and even more complex problem arises when considering the control of UMVs from moving platforms. One possibility of this is a man portable system being controlled as the operator is on the run. The operator, now the moving control platform, must operate a UMV while actively maneuvering his/her own body. An alternative scenario involves a UMV operator controlling the UMV from a station located in a moving vehicle. Operators must maintain spatial orientation and awareness of the UMV, while simultaneously sensing and understanding the dynamics of their own vehicle [1].

The lack of proprioceptive feedback inherent with UMV control can increase the workload for operators trying to maintain spatial orientation and awareness. Sensory information afforded an operator is drastically reduced and delivered almost entirely through the visual channel. Operators controlling UMs from moving platforms receive sensation cues completely independent (and often contradictory) from the vehicle being remotely controlled. This problem is compounded by the fact that the operating environments of the vehicles may be different and could change during the duration of the operator's control of the UMV. For example, an operator controlling a UAV must maintain spatial orientation and awareness of the UAV, while possibly operating from an air, ground, sea, or underwater vehicle. The proprioceptive cues of the ground, sea, or underwater environments can vary greatly from those of the aerial environment and would compound the mismatch of cues, increasing the difficulty of controlling a UMV and potentially leading to motion sickness.

In the above scenarios, the operator is simply operating the UMV while another operator controls the platform containing the UMV control station. However, it is also plausible that a single operator will directly control a vehicle (or his/her own body motion) while also attempting to control one or more UMs. This presents some unique challenges [1]. While it may reduce manpower and equipment needs, it may also require some control devices and display surfaces to act as inputs and displays for both the manned and unmanned vehicles. Issues emerge as to how best to switch the control and display between the vehicles, and which input devices and display surfaces can be used for both vehicles and which should be solely dedicated. This becomes an issue of supervisory control – to what degree does the operator need direct control and what areas of operation should be made autonomous?

Regardless of who is controlling the operator's vehicle, certain key concerns have been identified by [2] that must be addressed for UMV operations from a moving platform:

- How should spatial information about own-vehicle and controlled vehicle(s) be displayed to the UMV operator?
- Can individual differences in spatial orientation and mental rotation be used as criteria for selecting and assigning UMV operators?
- What types of training and simulation systems are necessary to develop the necessary skills to manage complex multi-vehicle dynamics?

In addition to the challenges of navigation/spatial orientation, other issues of concern are motion sickness, biodynamic interference with manual control, and head-mounted display (HMD) bounce. Motion sickness can occur when the visual cues of motion differ from those perceived by the inner ear, creating a sensory conflict [3]. Motion sickness can include nausea, dizziness, disorientation, and increased stomach awareness. Another issue is that of biodynamic interference, or, the input to manual control devices from the shock and vibration of rough terrain, transmitted from the vehicle to the operator and into the controls. This is especially common in UGV operations. And finally, HMD bounce refers to the phenomena of HMDs resonating at certain frequencies of vertical axis vibration, which are often found in ground vehicles [4]. The HMDs "bounce" relative to the face and eyes of an operator, degrading visual performance.

Below is a general discussion of the physical ergonomic aspects of mobile (and fixed) UAV control stations. This is followed by a discussion of a few of the specific issues surrounding the control of UAVs from an air-based control station.

6.7.2.1 Physical Ergonomic Aspects

This section discusses physical ergonomic aspects to be considered to optimize working conditions for mobile and fixed UAV workplaces based on lessons learned in the design and testing of workplaces. The discussion

will give insight in important issues in a general sense; however, detailed solutions will not be given. These details can be found in applicable handbooks, literature, reports, and such. Most of the issues mentioned below may be recognized as common sense. However, recent experience has shown that even common sense is commonly overlooked.

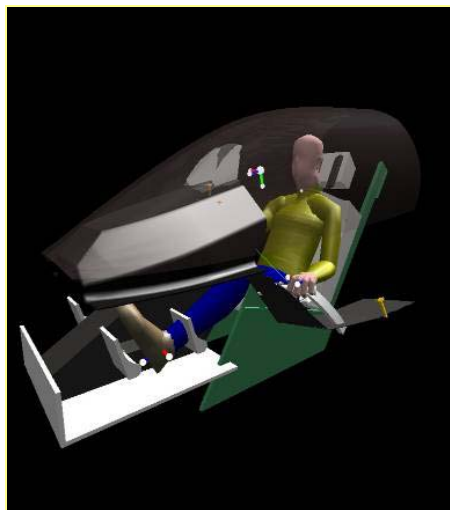
The physical ergonomic aspects include: anthropometry, biomechanics, climate control, workplace lighting, vibrations/accelerations, and control and display placement. The *fixed workplaces* are defined as shelters/containers with one or more UAV (control) workplaces. These shelters/containers are usually fixed on a certain location. However, it is also possible that these workstations will be operational during displacements; hence, they become *mobile workplaces*. The *portable workplaces* described here are in effect soldiers equipped with devices to assess information coming from the UAVs or even to control the UAVs.

6.7.2.1.1 Fixed and Mobile Workstations

6.7.2.1.1.1 Anthropometry

A common experience, at TNO Defence, Security & Safety, is that ergonomic specialists are asked to test the anthropometrics of a workplace once the design is more or less frozen without any prior involvement during the already fulfilled design process. The outcome of these tests is usually disappointing because the physical human operator is not considered properly: the operators do not fit, tall operators have to be shoehorned in and small operators can not reach applicable controls and displays.

Even more, the specialist's remarks may be such that an easy improvement of the workplace tested is not possible, invoking the need for drastic and costly design changes to the workplace. The most common cause for all this is that anthropometrics have not been considered properly during design activities despite commonly available human modelling techniques (see Figure 6-35). The most basic approach to overcome this issue is to set clear and proper anthropometric requirements once starting a new project, to assess these anthropometric requirements once developed and finally, to test the actual result using digital modelling, prototypes and/or mock-ups.



**Figure 6-35: An Example of a Digital Human Modelling System:
A Manikin in a CAD Model of the F16.**

Today, the use of statistical boundaries, or percentiles, is being replaced by “cases”. These cases define the boundaries based on manikins that have to be accommodated. The advantage of cases is that they are more accurate, give a better accommodation result and they are easily embedded into currently used human modeling techniques.

6.7.2.1.1.2 Biomechanics

Frequently, the following question is put forward: what is the amount of force that a P5 female can exert? The question implies, in most cases, that small females are weak. However, it must be noted that size/stature and force are not correlated at all! There are small females that can exert more force than their tall male colleagues and vice versa. On the other hand, it must be noted that the reach capabilities of smaller persons are more limited, possibly affecting the amount of force to be exerted.

Biomechanics come into play for UAV control stations when thinking about antennas that have to be erected and while deploying a launch bed for the UAVs themselves. These riggings usually require a lot of energy before they are effectively deployed. The amount of energy and forces needed must be in accordance with the user population capabilities. More often, the situation occurs that there is a mismatch. Again, there is a basic approach to prevent mismatches taking place: set biomechanic requirements, assess these issues when developing, and finally qualify the design in field tests on prototypes/mock-ups.

6.7.2.1.1.3 Climate Control

Climatic requirements are usually well defined and tested. For instance, an entire shelter including its equipment is tested in a climatic room under certain conditions (e.g., A1, hot dry conditions, STANAG 2895 [8]) with a positive result. However, in the actual deployment, under A1 conditions it becomes clear that the required temperature cannot be reached: in effect it is too hot. The mistake, often experienced at TNO Defence, Security & Safety, is that the test settings do not represent the actual working conditions because the energy dissipated by the operators (about 1.3 kW per person) is not taken into account. The solution is to be very critical for climatic test, and to make sure that the testing conditions do represent actual working conditions, using all equipment, using all heat producing elements, etc.

6.7.2.1.1.4 Lighting and Colours

Displays are commonly used in today's workplaces. Blackout lighting (blue or red light) systems are also commonly used in control stations to cope with certain tactical conditions. One must make sure that the information shown on the displays is in accordance with the blackout lighting conditions. Recent experience, at TNO Defence, Security & Safety, showed that friendly troops, displayed in green, were not recognizable under red light conditions. Other elements, like enemy front lines, even disappeared under these conditions. Another problem became apparent after a short while: certain operators (about 8 to 10% of all males) could not see certain elements at all. These operators were unable to distinguish certain colors: they were colour blind. Therefore, a strong directive: take tactical lighting conditions and colour blindness into account in the design of displayed information in order to prevent any problems.

6.7.2.1.1.5 Mobile Workplaces

Designing workplaces for static conditions poses enough challenges already before an acceptable compromise is found – but an even bigger challenge becomes apparent when the workplaces have to be used during displacements as well. Aspects such as HIC (head injury criteria) and legislation for safety belts come into play. This section will not discuss all the rules, but will discuss an elementary issue for the operator. It is clear

that safety belts are elementary for mobile workplaces. The actual choice for a retractable or fixed safety belt has a strong influence on possibility to work effectively. Recent experience, at TNO Defence, Security & Safety, confronted operators with fixed belts disabling them to reach the controls and to read any display information: they were fixed to their seats and could not reach any workplace element. Therefore, a strong word of advice: opt at first for a retractable safety belt and make sure that the operator is not hampered while working due to any safety system.

6.7.2.1.1.6 Nuclear, Biological and Chemical (NBC) Conditions

It is a fact that our troops are confronted with NBC conditions. Even under these circumstances one must be able, when wearing protective gear, to effectively operate UAVs. It is clear that protective gear, especially the NBC gloves, affect dexterity. And the amount of energy that can be exerted is affected as well due to the isolating properties of the suit and the limited breathing possibilities when wearing a mask. All these elements combined will have to be taken into account for all operations inside *and outside* (e.g., when rigging antenna arrays, setting the UAV launch station) the UAV control station.

6.7.2.1.2 Portable UAV Workstations

There seems to be an apparent need for field operators (e.g., soldiers, policemen, firefighters), to have a mobile office. In some cases, the operator is simply equipped with an advanced mobile telephone. In other cases they have to carry a complete laptop while working. The result is, in most cases, not fully satisfactory: the equipment does not perform properly (e.g., one cannot access the worldwide web properly using a mobile phone due to the limited size of the display and input media) or it is simply too bulky (e.g., a complete laptop, including power source, is not compatible with standard battlefield operations). Recently, a system was developed as a prototype system, by TNO Defence, Security & Safety, with a helmet integrated vision device and a small touchpad as input device, in the Soldier Modernization Program (see Figure 6-36). This system basically focuses on the needs for the operator in the battlefield: some operators only need a display for a short period of time (e.g., a soldier needing information concerning his/her whereabouts), other operators need more information (e.g., a group commander needs more information and has an additional need to input data).

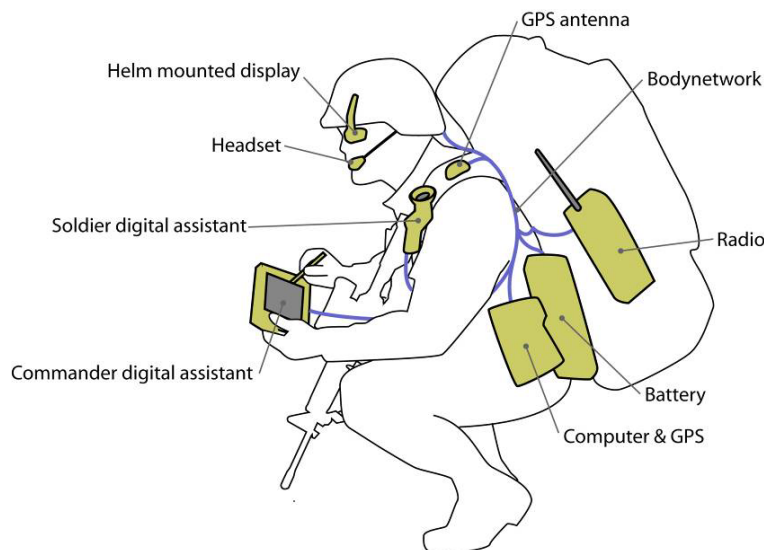


Figure 6-36: A Soldier Equipped with Various Portable Systems for Advanced Field Operations.

The basic thought behind this system is that it is fine-tuned to the operator's needs. This system is not yet used or tested in operational circumstances; this will take place in the beginning of 2006. An elementary issue to be focused on is the effect of the new system on battlefield operations. It is already apparent that some users will have to change their standard operational procedures because they will have an additional task to perform: the task of information management.

6.7.2.2 Manned-Unmanned UAV Teaming from Air-Based Control Station

Most currently used UAVs are controlled from a (closed) container Ground Control Station (GCS). The GCS operators are generally concerned with only one UAV system. Here, the Mission Commander communicates the acquired intelligence to other units. In past years, experimental setups have been developed in which the information from the UAV sensors is more directly presented to aircraft during a mission. A pioneer project was U.S. Army's AMUST (Airborne Manned Unmanned System Technology [5]). Here, an Apache helicopter and a Hunter UAV form a team, where the UAV may perform all kinds of useful sidekick tasks, such as reconnaissance, laser-designation of targets and acting as decoy. The UAV can be either controlled from a GCS or by the Apache's co-pilot/gunner.

The AMUST concept adds to the complexity of maintaining situation awareness: the operator (the co-pilot/gunner) has to deal with at least three spatial frames of reference, namely the world, the helicopter and the UAV. Our first research questions were: Is such a co-pilot able to build up situation awareness involving multiple platforms, and how is this situation awareness affected by being on board one of the platforms? These questions were investigated in the first study described below.

In the AMUST concept, the co-pilot interacts with the UAV. In future operation concepts, e.g., Network Enabling Capability, 'sensors' and 'shooters' are allocated more dynamically. In a second study, briefly described here as well, we investigated the possible benefits for the pilot in having available a UAV image in the cockpit when performing a simulated Close Air Support mission.

6.7.2.2.1 Multi-Platform Situation Awareness

De Vries and Jansen [6] conducted a simulator experiment to assess the situation awareness of a co-pilot who controls a UAV platform while on-board a moving platform, in this case a helicopter. The co-pilot has to integrate the reference frame of the UAV with that of his own platform. Participants serving as UAV operators were seated behind a UAV console situated in a helicopter mock-up. The console displayed an electronic map of the geographical situation of a UAV, helicopter and a few other objects. For each simulator trial, the participants watched the movements on the electronic map display for a few minutes after which their situation awareness was assessed using an electronic questionnaire. Questions could be related to an earth-fixed coordinate system (compass) or be orientation-based (relative). Questions addressed the helicopter, UAV, or a formation of tanks. The main dependent measurement was angular error, i.e., the difference between the direction indicated by the participant and the real direction. The main experimental manipulation was a representation of the outside scenery on a 180-degree cylinder-shaped screen. Indicators were presented to show the movements of the helicopter. The simulation was presented in two work environments for the UAV operator: in a ground control station setting and on-board a moving platform (helicopter).

The most important results from this study are presented in Figure 6-37. The Figure depicts for the six different question types the angular error in indicating the location of an object. For most of the question types, the right bars (corresponding with the condition of the UAV operator aboard the helicopter) are much higher than the left bars (corresponding with the situation of an operator in a ground control station).

This indicates that in general terms, performance is worse in conditions in which we simulated that the UAV operator is aboard one of the moving platforms (except when questions were asked with respect to the platform itself). Note that the task itself is not different for the stationary and moving operator: just look at the electronic map and build up a spatial awareness as good as possible. The results revealed that it is indeed more problematic to maintain a multi-platform situation awareness while being aboard a moving platform. Apparently, when the operator is in a situation where one spatial frame of reference is dominant (i.e., while aboard a helicopter), it is very hard to process spatial information from other perspectives.

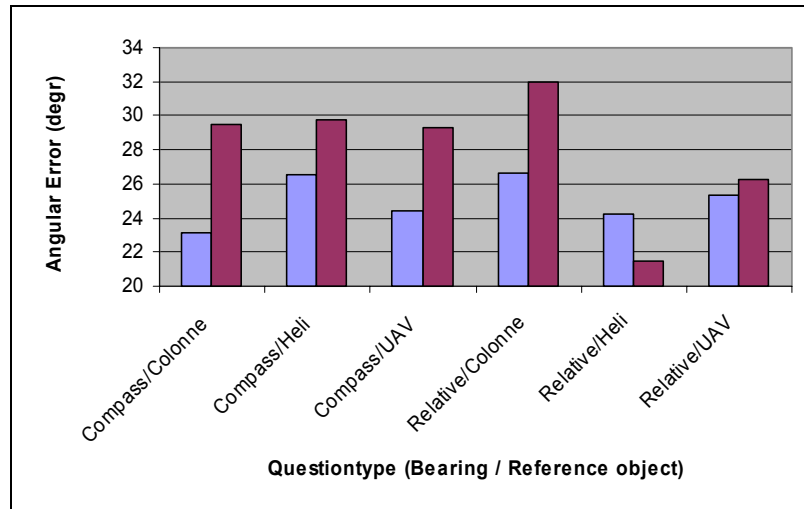


Figure 6-37: Angular Error in Indicating an Object Location for the Six Question Types.
The left (blue) bars refer to the situation of an operator in a ground control station;
the right (red) bars to the situation of an operator aboard a simulated aircraft.

6.7.2.2.2 Using Real-Time UAV Images while Conducting a Close Air Support Mission

The above research has shown that performance drops when multiple reference frames need to be integrated while performing a spatial situation awareness task. In a second experiment [7], a more critical situation was investigated in which misinterpretation of spatial information directly resulted in failure of a simulated Close Air Support mission. A situation was investigated in which a pilot used a UAV image, presented in the cockpit. As the UAV camera has a viewpoint that differs from that of the pilot, the pilot's interpretation of the spatial layout of the scenery may be prone to error (e.g., if the UAV flies in the opposite direction, the object on the left in the sensor image is actually on the right in the pilot's perspective). The aim of the research was to minimize the chance of such errors by rotating the UAV sensor image such that its orientation is always aligned with the pilot's spatial frame of reference. In this study, four military pilots performed several Close Air Support missions with six different display configurations. The orientation of the electronic map was either North-Up or Heading-Up. The UAV sensor image was either absent, present, but non-aligned (i.e., unadjusted image orientation: the image is presented as seen from the UAV viewpoint), or present and aligned with the orientation of the electronic map (adjusted image orientation: the image was presented as if the sensor was placed on the helicopter).

The pilots reported that they generally preferred the Aligned UAV sensor image in combination with a Heading-Up map. This preference was reflected in their performance, depicted in Figure 6-38: targets were identified twice as fast. Strikingly, flying performance was also better when an aligned UAV image was used.

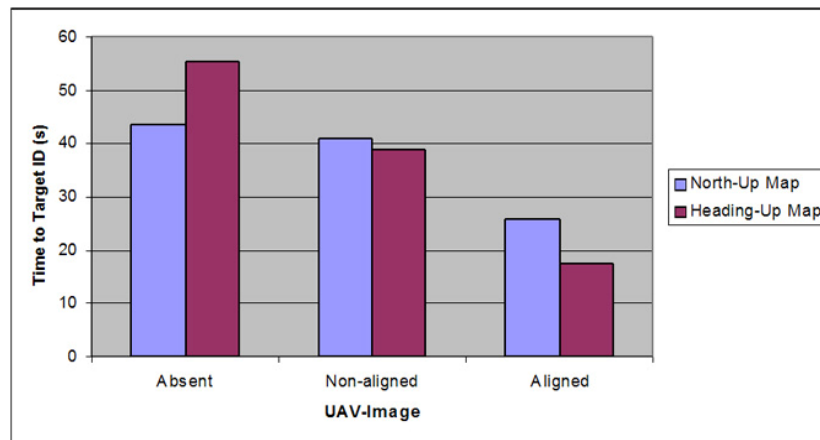


Figure 6-38: Time to Target Identifications for the Six Display Configurations.

6.7.2.2.3 Conclusions

In comparing the (simulated) situations of a stationary UAV operator and a moving UAV operator it appeared that it is very hard to process spatial information from multiple perspectives simultaneously when one perspective is dominant (here, when being aboard a helicopter). In experiments on presenting UAV images in the cockpit while performing a Close Air Support mission it was investigated whether the interpretation of (the non-dominant) UAV image information was facilitated by aligning that perspective with the dominant perspective of the helicopter. Based on the results and pilot's reports it was concluded that the availability of a UAV sensor image in the cockpit of an aircraft only improves mission performance when its orientation is aligned with the aircraft.

6.7.2.3 References for UMV Operation from Moving Platforms

- [1] Walter, B.E., Knutzon, J.S., Sannier, A.V. and Oliver, J.H. (2004). Virtual UAV Ground Control Station. Proceedings of the American Institute of Aeronautics and Astronautics: 3rd "Unmanned Unlimited" Technical Conference, Workshop and Exhibit. AIAA 2004-6320.
- [2] McCauley, M.E. and Matsangas, P. (2004). "Human Systems Integration and Automation Issue in Small Unmanned Aerial Vehicles." Naval Postgraduate School.
- [3] Reason, J. and Brand, J.J. (1975). Motion Sickness. London: Academic Press.
- [4] Sharkey, T.J., McCauley, M.E., Schwirzke, M.F.J., Casper, P. and Hennessy, R.T. (1995). The Effects of Whole Body Motion, Head Mounted Display, and Hand Control Device on Tracking Performance. Warren, MI: U.S. Army Tank and Automotive Command.
- [5] Fayaud, G.R. (2001). The airborne manned unmanned system. *Unmanned Systems*, 19(4), 16-21.
- [6] de Vries, S.C. and Jansen, C. (2002). Situational awareness of UAV operators onboard of moving platforms. Proceedings of the International Conference on Human-Computer Interaction in Aeronautics, HCI-Aero 2002 Cambridge, MA, 23-25 October 2002 (S. Chatty, J. Hansman, and G. Boy, Eds). AAAI Press: Menlo Park, CA. pp. 144-147.

- [7] Jansen, C., de Vries, S.C. and Duistermaat, M. (2005). Presenting images from an unmanned aerial vehicle in an attack helicopter cockpit. Report DV3 2005-A16. Soesterberg, The Netherlands: TNO Defence, Security and Safety.
- [8] North Atlantic Treaty Organisation, (1990). Standardization Agreement: Extreme Climatic Conditions and Derived Conditions for Use in Defining Design/Test Criteria for NATO Forces Materiel, MAS/048-MMS/2895.

6.7.3 Other Issues: Latency, Trust, Bandwidth

As well as the factors mentioned above, there are also a number of other considerations that have human factors implications for a UMV system. This section of the report summarises a few of the factors that are more likely to be encountered.

6.7.3.1 Latency

In this instance, latency refers to the time delay between the UMV operator making a control input and the feedback received by the operator from the system to confirm that the control input has had an effect. Such latencies are particularly noticeable, in the UMV context, when pointing sensors and issuing commands.

Early research suggested that as latencies increased, operator performance decreased in a linear fashion [3], however later research showed this to be oversimplifying the issue. For example, Asbery [1] varied the latency in feedback between 28 ms and 2000 ms for a target tracking task, and found that there was a sharp initial decrease in performance with latencies up to 100 ms with the detriment on performance diminishing thereafter until 1000 ms where it levelled out at a consistently poor level. This suggests that the claim of a linear relationship to be inaccurate. Asbery also found that the operators employed strategies to cope with a high degree of delay between action and response. When latencies increased, the participants seemed to lose sense of the orientation of the camera system. To overcome this, some participants delayed their inputs until the camera ‘caught up’ with their previous action. In general, trajectories became oscillatory in nature because of the overshoot generated by the high latency.

It has also been shown that latency may have very precise ‘effect boundaries’ where a certain range of latencies will have the largest effect on performance at a task. For example, studies have shown that for a simple control task (e.g., man-in-the loop UMV control) there is no noticeable effect of latency between 0 and 500 ms, but a sharp decrease in operator performance between 500 ms and 1000 ms. Similar patterns of results have been found in a trials investigating pilot’s landing ability using synthetic visual aids. In general, the findings from research in this area support the view that the impact a particular level of latency will have on a task is linked to the degree of control required to complete the task. A relatively low latency will have a much more pronounced effect on a task involving the operator making many minor adjustments than a task involving only general large-scale control movements.

Research on latency in virtual reality systems [2] found that latencies in update following a head movement had a more profound effect on the visual system than latencies following hand movement. It was suggested by the researchers that because hand movement is a feed-forward process, there is relatively little effect due to latency, as the control is not based on feedback from the visual system. On tasks that require visual feedback to monitor the results of actions, latencies have a much more noticeable effect.

To conclude, latencies do not correlate linearly with performance. They have specific ‘effect boundaries’ that will depend on the type of task undertaken. Latencies may have a less pronounced effect if the task requires

only feed-forward control and not visual feedback. Tasks requiring fine motor control are in general more severely impacted by shorter latency periods. Specific guidance on the likely acceptable level of latency for a given type of task is given in various standards. For example, UK Defence Standard 00-25 [4] lists the following recommendations for acceptable response times associated with human-computer interaction:

- <50 ms From movement of pointing device to movement of cursor or marker.
- 100 ms Pressing a key to character being displayed.
- 200 ms Selection of displayed object (field, button, menu option) to object appearing as selected; Selection of menu header to menu being displayed; Selection of scroll button to completion of scroll of one line of text.
- 1-2 s Completion of user input to display of error indication.
- 2 s Request for next page of information to completion of one page change; Completion of user input to completion of simple process; Completion of display manipulation request to completion of display change (e.g., open a window; zoom).

6.7.3.2 Trust

The UMV operator is required to make accurate and timely decisions. As they are physically removed from the vehicle they are controlling, they are reliant on the information provided to them from external sources, most likely from the UMV itself, and their experience of similar situations to make these decisions.

Trust relates to the operators' willingness to rely on the information presented. Clearly the operators must trust that the information provided is accurate if they are to use it effectively in the decision making process, rather than trying to 'second-guess' the situation and relying solely on previous experience. In addition, in UMV systems that rely on the operator acting as a 'system supervisor', the operator must trust that the automation in the system is carrying out the tasks associated to it in order for this mode of operation to work effectively. Without this level of trust, the operators' workload would increase significantly as they attempt to monitor the system too closely.

A discussion on decision making is outside the scope of this report, although the reader is encouraged to read one of the many texts available on human decision making. Instead this report will focus on issues and research directly relating to trust.

There are a number of theories of trust. For example, Muir [8] noted that the study of trust was under researched in the engineering psychology literature. She suggested that while the research may be lacking for trust in Human Machine Interaction (HMI), it would be possible to extend existing theories of interpersonal trust. Muir built on the theories of Rempel, Holmes and Zanna [9] to propose a three factor theory of how trust develops. Early on in the operator-machine relationship, the *predictability* of the system's decision is important in building trust. A system that makes unpredictable decisions will not be trusted. Once the system is perceived as predictable, an operator will trust a system more if it is deemed *dependable*. Dependability evolves over time as the system operator makes generalisations about the specific actions of the system to a broader set of attributes of the system. Dependability will be particularly strong if the machine is able to perform accurately under risky situations. The final stage involved the development of *faith*, the belief that the system will be dependable in the future. During this stage of the 'relationship' between the operator and the UMV, transparency in the UMV's decisions will be important in maintaining trust.

This, and other models of trust applicable to UMV systems, tends to neglect the characteristics of the operator in favor of aspects of the system. For example Kelley et al.'s model [10] does take the operator into account to a limited degree. In this model, trust is gained and influenced by the *competence* of the system (as summarised by earlier models, described above), *understanding* and *self-confidence*. Self-confidence contains factors such as skills, experience and faith which directly relate to the operator of the system. Similarly understanding contains factors that arise as a result of the operator and UMV in combination; predictability and familiarity for example. This model was originally constructed to understand trust within the Air Traffic Management (ATM) environment, although it can be applied to many areas of human machine interface. The model also examines trust at a broader level, fitting it into a model of system acceptability alongside factors of teamwork and situation awareness (Figure 6-39).

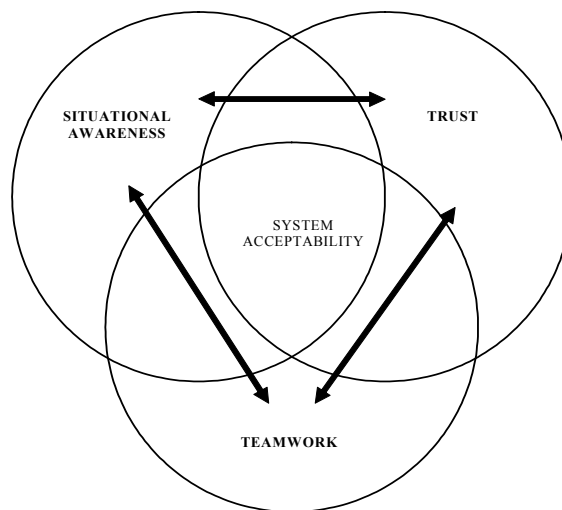


Figure 6-39: Trust in ATM Context (Kelley et al., [10]).

Most models are lacking, as they generally ignore the properties of the operator. Others include the operator, but only when factors such as confidence and training have been explored [5]. Additional attributes of the operator may also have an impact such as individual differences in overall propensity to trust.

6.7.3.3 Bandwidth and Update Rate

The bandwidth of the communication link between the operator and the UMV and the update rate of the information that is provided are important considerations in UMV system design. In order to control a system effectively, the operator requires the right amount of information to be provided at the right time.

Bandwidth limits the size of the information passed down the communications link, whilst update rate refers to how often the information is refreshed. Both are interlinked; low bandwidth links may impose a limit on the speed that information can be transmitted. Bandwidth may be restricted by technological limitations or by operational restraints, for example because of a need to operate the system covertly.

Work completed by Haduch [7] suggests that the quality of feedback provided to an operator will effect how the UMV is operated. Of all the senses, visual feedback is most often favored by system designers for feedback, possibly because it is perceived as being the most informative. Haduch suggests that it may be

possible to utilise a form of cross-modal communication; using audio communication rather than visual to represent speed for example. Haduch also suggests ways of reducing the communications bandwidth required to operate a UMV. A simple example of this is reproducing vehicle generated sounds at the control station. This way, the actual data of the sound of the wheels spinning, for example, need not be sent (as this could place heavy demands on the bandwidth available), but merely a message indicating to the control station to make a sound of wheels spinning. Such a system may not be applicable to all situations, but will lessen the need for large communication bandwidths in many situations.

Bandwidth requirements will also vary depending on the operators' role. A supervisory role with intervention from the operator only in emergencies, will cope much better with smaller bandwidth communications links than a system that requires full operator in the loop control. This implies greater implementation of automation into UMGVs which in turn has human factors considerations (e.g., see above), but will lessen bandwidth requirements.

Any bandwidth reduction would initially require investigation into what the key information needed for the task was. This information is relatively lacking in the literature, although this is most probably because the key information will be highly task dependant [6].

6.7.3.4 References for Other Issues

- [1] Asbery, R. (1997). The Design, Development and Evaluation of an Active Stereoscopic Telepresence System. PhD Thesis. Guildford: University of Surrey.
- [2] Kawara, T., Masao, O. and Yoshizawa, T. (1996). Effects on visual functions during tasks of object handling in virtual environment with an head mounted display. *Ergonomics*, Vol. 39, No. 11, 1370-1380.
- [3] Warrick, M.J. (1949). Effect of transmission-type control lags on tracking accuracy. (Technical Report 5916). Dayton, Ohio: Wright-Patterson Air Force Base, Air Force, USAF Air Material Command.
- [4] Defence Standard 00-25, Human Factors for Designers of Systems (Part 19, page 163), Issue 1.0. Defence Procurement Agency.
- [5] Adams, B., Bruyn, L., Houde, S. and Angelopoulos, P. (2003). Trust in Automated Systems Literature Review. Humansystems Inc. on behalf of Defence Research and Development Canada.
- [6] Willis, A.R., Beagley, N., Davies, I. and Stringer, N. (1999). Remotely Piloted Vehicles: A Review of Human Factors Research and Recommendations for Research. DERA/CHS/PPD/CR990013, Defence Evaluation and Research Agency.
- [7] Haduch, T.W. (1993). Operator interaction with Unmanned Ground Vehicles (UGV) (with limited data transmission), In: Smith, M.J. and Salvendy, G. (Editors), *Human-Computer Interaction: Applications and Case Studies*, Amsterdam: Elsevier.
- [8] Muir, B.M. (1994). Trust in automation: Part 1. Theoretical issues in the study of trust and human intervention in automated systems. *Ergonomics*, 37 (11), pp. 1905-1922.
- [9] Rempel, J.K., Holmes, J.G. and Zanna, M.P. (1985). Trust in close relationships. *Journal of Personality and Social Psychology*, 49, pp. 95-112.

- [10] Kelly, C., Boardman, M., Goillau, P. and Jeannot, E. (2001). Principles and Guidelines for the Development of Trust in Future ATM Systems: A Literature Review, European Organisation for the Safety of Air Navigation, pp. 1-48.

6.8 SUMMARY

This chapter described many candidate control/display technologies that are potentially applicable to UMV operator interface design and detailed other important design considerations. However, since UMVs encompass a very broad range of vehicle types, capabilities, mission contexts, and environmental constraints/affordances, it is important that any UMV operator interface design follow a multi-disciplinary user-centered design process. The goal of user-centered design is to ensure the final design meets the users' needs and expectations. The process of requirements definition (user profiles, work flow, task analysis, and information architecture) and repeated interface design development and iteration (through multiple usability assessments and formal evaluations) will increase the likelihood of obtaining a truly functional and easy-to-use interface.

Other key conclusions can be drawn from this chapter, besides the importance of user-centered design. First, the potential importance of mission-specific multi-modal interfaces to UMVs is highlighted. Since UMV operators are currently limited to a reduced stream of sensory feedback delivered almost exclusively through the visual channel, there is reason to believe that situation awareness and performance may be improved through increased multi-sensory stimulation. These improvements might stem from an increase in the operator's sense of 'presence' in the remote environment, from increased information throughput afforded by effective use of multi-sensory stimulation, and/or a more intuitive presentation/control of information, and thus improved performance over conventional visual interface practices. Technologies such as spatialized audio, haptic/tactile stimulation, and speech recognition systems appear especially relevant to multi-UMV operations.

Additionally, as UMVs become more automated/autonomous and single operator control of multiple UMVs is mandated, the importance of the human-automation interface becomes paramount. As mentioned above and in Chapter 7, there is a wealth of potentially negative effects associated with human-automation systems that have significant implications for the operator interface design. Automation must be designed to augment, not hinder, human capabilities. Operator interfaces must provide rapid visibility into the current status and future plans of automation for shared human-automation situation awareness. Additionally, intelligent decision support interfaces will need to be designed such as to allow independent operator assessment of the situation as well as the rationale for any automated classifications/recommendations.

Finally, the chapter clearly indicates several areas in need of further research. These areas include the relative costs/benefits of the various control/display technologies identified for particular classes of UMV applications (air, ground, sea), a better understanding regarding the application of multi-modal interface technology for UAV operator interfaces, the issues surrounding human supervisory control, and the design of effective decision support interfaces for enabled multi-UMV control.



Chapter 7 – HUMAN AUTOMATION INTEGRATION

Chapter Lead: S. Galster

**Contributors: M. Barnes, K. Cosenzo, S. Galster, E. Hollnagel,
C. Miller, R. Parasuraman, J. Reising, R. Taylor, L. van Breda**

7.1 INTRODUCTION

Many versions of future concept of operations (CONOPS) rely heavily on UMVs. The pressure to take the human out of immediate control of these vehicles is being driven by several factors. These factors include a reduction in cost for the production and maintenance of the vehicle, operational viability in extreme environments, and the public pressure to keep soldiers further away from immediate harm. In addition to adding more UMVs, there is also a push to have these vehicles perform more complex tasks than they are currently required to perform. These two factors, adding more UMVs and having them perform more complex tasks, will not be realized without augmenting the current structure of control. One way to achieve this augmentation is through the utilization of automation. The automation may be applied on the vehicle itself, through the interface controlling the vehicle, through system design or in any amalgamation of these approaches. Automation, if applied in a responsible and judicious manner, will enable the acquisition of capabilities that will be required to operate under near and far-term CONOPS.

The focus of this chapter is the discussion of the past, present and future automation integration challenges that are faced when adopting a human centric design philosophy. Topics will include the identification and discussion of specific problematic areas that have evolved and will bring to bear the lessons learned as automation was integrated into other domains such as flight operations, air traffic control, and process control for example. The lessons learned may not signify that a particular problem area has been “solved”, but may point out that the area deserves consideration when evaluating trade-offs in the system design and engineering process. The anecdotal, operational, theoretical and empirical work completed thus far all provide a sound foundation that should serve as a starting point for human automation integration in the UMV domain. This domain may have specific challenges or specific opportunities available, both now and in the future, to explore and expand the base of human and automation integration knowledge. The remainder of this introduction will focus on some of the more salient areas in the integration problem space. These topics and others will be addressed in various sections throughout the chapter.

7.1.1 Problems with Supervisory Control Tasks

Vehicle control may be considered as a hierarchically structured set of functions. Plan conception and plan selection activities are performed in the navigation function, verification and adjustment of the short-term voyage progress are performed in the guidance function, and typical closed-loop control activities are performed in the control function. *Supervisory control* of vehicles deals with automated vehicle control functions to a large extent. Current technology is not yet prepared to autonomously perform mission guidance under dynamically changing environmental conditions, although navigation, guidance and control functions are widely automated. The operator, who may observe the controlled process, acts as a manager who supervises the system and interacts with the automated system by performing corrective actions. The human operator in current architectures is the primary responsible factor in terms of goal-driven decision-making, and thereby specifying the constraints and demands settings for the automated system.

It is known, however, that supervisory control systems have certain limitations in performance, either on the operator's side due to human capacity limitations or induced by deficiencies of the automation, causing human error intensified by the inability of the automation to perform on the higher level of problem-solving.

7.1.2 Function Allocation

Consider the development of human roles and automation from the traditional "*Left-over principle*", through human engineering optimising *compensatory* principle with human monitoring (Fitts lists), to contemporary *complementary* principle arising from human-computer co-operation/collaboration. Now function allocation can be dynamic according to external system functions, efficiency and system boundary conditions. Levels of autonomy provide bounding of the decision authority and behaviour to promote trust. Key questions:

- Should the human monitor the (technical) system given that humans are poor monitors?
- Should the (technical) system monitor the human?
- If so what roles should the human play and what are their responsibilities?
- Are humans included in systems just to deal with those functions that engineers can not automate?

7.1.3 Levels of Automation

For designing supervisory control, possible structures for the allocation of decision-making tasks between human and computers are complex (up to 10 levels). These have been applied to stage models of human information processing functions (information acquisition, analysis, decision selection, action implementation).

7.1.4 Pilots Associate Levels of Autonomy

Autonomy can be defined simply as the capability to make decisions. Pilots Associate (PA) Levels of Autonomy (LOA) and prime directives recognise the need for the operator/pilot to remain in charge. PA provides selectable LOA (Inactive, Standby, Advisor, Assistant, Associate) defined by operational relationships with bounded structure, but this needs to be readily communicable.

7.1.5 Cognitive Cockpit PACT

User knowledge acquisition produces a practical, communicable set of assisted PACT levels (At Call, Advisory, In Support, Direct Support) for variable and adaptive decision support/automation, supporting situation assessment, decision making and action. Research focus shifts to developing practical procedures for pre-assigning functions and tasks, operator initiated real-time changes, and triggering level changes from context-sensitive adaptive rules. Scripts and play-book tools for delegation of tasks/policy become relevant.

7.1.6 UAV/UCAV Autonomy

PACT LOA have been applied to the management of multiple UAVs to help pilot/ground operator workload. DARPA UAV programmes use four levels of autonomy with intermediate levels of exception and consent (UCAV), and veto and permissive (ICAV). UCAV research focus moves to multiple collaborating, autonomous groups covering complimentary, co-ordinated and co-operative planning and interactions.

7.1.7 Multi-Agent Adjustable Autonomy

Dynamic adaptive and adjustable autonomy is proposed for multi-agent intelligent systems for distributed problem solving structures in complex dynamic environments. Agents have self-direction and goals with capability to form, modify or dissolve the agent organisation. Degree of autonomy becomes linked to individual goal. Focus moves to the decision process for how a goal is pursued free from intervention, oversight or control by another agent. Autonomy with respect to goals is on a variable scale (consensus, master, local, command). Issues become rules for transfer of control, communication protocols, interaction styles, and cognitive strategies for reasoning with adjustable autonomy in operating context.

7.2 AUTOMATION AND HUMAN PERFORMANCE

Through the introduction of automation, the supervision of multiple functions is more and more assigned to a single human operator, the 'process manager' or 'supervisor', who is assisted by a process information system. Consequently, the level of direct involvement of the human operator with the actual process is decreasing. It must be realised that there is ample evidence that lack of attention to the human aspects in early phases of the development process of a system may result in wrong usability. It is therefore essential to consider in the pre-design phase, to what extent the machines should be made automatic and how this affects human factors related issues, with the purpose to minimise the risk of errors and to optimise system performance. The following deals with these human factors considerations, showing the areas that deserve attention.

7.2.1 Humans and Unmanned Military Vehicle

Current UMVs can operate in a more or less autonomous way. This means that the operator-supervisor is no longer directly operating the UMV directly, but parts of the work (semi-autonomous or semi-automatic) or the entire job (fully automatic or autonomous) are operated by the machine itself. In the consideration of semi-automatic operation, there may be various levels of human involvement. In semi-automatic systems, the system may address certain sub-tasks which are normally operated independently (e.g., with one command take-off and go to cruising altitude). As a next step, the machinery could perform complete well-defined tasks (e.g., perform a battle damage assessment task). As a next step, a more complicated set of tasks may be executed, such as fly back to base. Finally, a complete 'mission' may be run automatically. It may be clear that fully automatic systems may be very accurate in performing repetitive tasks. Yet, they typically lack flexibility.

At present, much effort is spent to the development of real-time process control systems as a means to increase the efficiency and the safety of automated systems. It is, however, important to maintain an operator-centred automation philosophy that overcomes limitations, enhances abilities and fosters acceptance when automated systems are introduced. Therefore, focus on human factors issues related to the automation is essential. Below, a generic list of issues is provided together with criteria that should be taken into account when automation is introduced.

In general, the user-centred design process starts with a function analysis, function allocation and task analysis process, in which the demands that UMV moving tasks put on the user, the identification of information to be processed and decisions to be made by the user, are determined. The opportunities provided by new technologies in performing UMV tasks have to be analyzed in terms of where and how they could support the human operator. For this purpose, a generic model of information transfer must be developed, which can be used to support the analysis. On the basis of this generic model, relevant issues are described which focus on

human factors aspects with respect to control and supervision of (semi-) autonomous systems. This must lead to a list of recommendations. Throughout the report, the relation with a practical situation is explained (i.e., UMV operation).

Technological developments more and more allow sub-systems of machinery to be automated. The potential benefits of automation express themselves in different areas: it can make the machines to perform the work faster and more accurate, it can reduce the fuel consumption and increase the economical utilization of the machines. Furthermore, automation can relieve the human operator from dull, repetitive or dangerous work, and reduce the workload. However, there are also potential drawbacks from a human factors point of view when automation is introduced. For example, in the cockpit of commercial airlines it appeared that automation lowered job satisfaction, induced human error, and caused a significant loss of skilled behavior. Parasuraman and Riley [1] give a summary that includes the use, misuse, disuse and abuse of automation. Stokes, Wickens and Kite [2, p. 101] stated that ‘a potential danger is to automate tasks that are easy or beneficial to automate, instead of those tasks which are eligible for automation from the operator’. This means that sometimes the overall performance of a system may be enlarged by allocating a certain function to a human, although an automaton would perform better on the specific function. This implies that evaluating the system as a whole with the operator in-the-loop is at least as important as evaluating the performance of individual automated subsystems. *“designing or automating a human-machine system rarely produces an acceptable result without extensive searches through alternative designs plus experimentation to evaluate overall system performance; there are no shortcuts to success”* [3, p. 1459].

In the literature, different definitions of automation are used. The most common definition is used by Wiener [4], Satchell [5], and many others: ‘Automation is concerned with replacing human functioning by machine functioning’. This applies for both partial and total replacement [6]. Despite the agreement on the definition of automation, several authors distinguish many sorts and levels of automation. Although these sorts and levels are not necessary to discuss the human factors involved in automation, they may be useful in understanding the conceptual frameworks and the complexity of the underlying knowledge domain. Wickens [7] distinguished automation for replacing the human, and automation for supporting the human; Wiener [4] distinguished automation of control tasks, and automation of monitoring functions (which can be divided into automation of detection, and automation of diagnosis). These distinctions are based on the different levels of human functioning, and resemble the approach of Sheridan [8]. The latter bases his conceptual framework upon the three levels as defined by the model of Rasmussen [9]: Skill based, rule based, knowledge based. Sheridan claims that for successful automation, one has to start at the skill based level; automation of tasks at the knowledge based level is exceptional.

Although the introduction of automation sometimes follows on the availability of new techniques and technological developments, it is also recognized that there are important potential advantages for the operator and the system output when human functions are transferred to a machine. Automations can simply be better in certain tasks, for example, to perform route planning tasks in order to minimize fuel usage [10,4]. Even simple automations may be faster, more accurate, more reliable, less stressful, less vulnerable for small errors, and cheaper than human operators. They even may be able to perform tasks, which the operator is able to specify, but not able to execute (including tele-operation). Important considerations may also be aimed at relieving the human from time consuming, dangerous, complex, tiring or dull (repetitive) tasks [2]. However, the main goal concerning the human operator is to reduce workload [3,11]. This may enhance both the well-being of the operator, and the performance of the total system. There are additional effects of automation, which are not directly the goal of the design process, but offer opportunities to further improve system performance (e.g., automation may offer possibilities to introduce on-line simulation of the work process; predictive displays may be used to support the anticipation process; ‘fail soft’ protection may prevent

operators and equipment to commit certain errors, limiting the influence of individual differences on system performance).

It may be clear that the role of the human operator is considered trivial by some, and critical by others; the fundamental nature and the characteristics of the interaction between operator and automated system is still a matter of debate and design evolution. This introduction underlines the importance of considering the human factor when automatic systems are introduced.

7.2.2 Human Factors and Automation

Automation may be introduced to replace or support operator functions at different levels. In the literature, various sub-divisions are made, ranging from 'no automation' to 'fully autonomous operation'. A useful subdivision was made in AGARD [6] with seven different levels of automation (i.e., no automation, manual augmented, manual augmented limited, co-operative, automatic pre-select, automatic select, and autonomous operation). In this Introduction, these levels of automation are applied to UMVs. An eighth level (unmanned operation) is added. Note that unmanned operation is possible at all levels of automation, however, this is not considered within the scope of this Introduction. Practical applications are suggested for each level of automation, and the implications with respect to human factors considerations are discussed.

1) No Automation

The system is manually operated without any automatic augmentation or support. The operator is performing activities using his human faculties (e.g., visual functions, mental activities, visual inspection, verbal communication). The control movements by the operator directly affect system output.

2) Manual Augmented

Manual control is augmented by an automatic system when an automatic system assists the operator by controlling simple activities (so-called low level activities). Examples are augmented systems that control a single system variable (e.g., speed, frequency, rpm, strength, pressure), or provide low level decision support (e.g., records images when desired).

3) Manual Augmented and Limited

Manual control is augmented and limited when an automatic system assists the operator by controlling low level activities such that over-control and control-errors are avoided. An example is the anti-lock brake system (ABS) in cars; the driver needs less pedal force to execute a brake action, and moreover, when a full stop manoeuvre is made, the braking action is limited in order to avoid break-out of the car. Another example is the speed-limiter in trucks; the truck will stop acceleration when a certain speed is reached, even when the gas pedal is pushed down further. An example in decision making support is the monitoring of input sequences (e.g., a car does not start the engine as long as it is put into gear).

4) Co-operative

Co-operative support of manual control is an automatic function with pre-selection of parameters and their values, in combination with manual control. An example is dynamic positioning of a ship during disturbances (e.g., in wind and water current). Another example is cruise control in cars; the driver selects the desired speed and the car will drive at that speed, irrespective of the road condition (e.g., highway or desert road, hill upward or downward). Note that co-operative support may be superimposed upon the

lower support levels to enable the operator to go beyond the installed limits when certain extreme control conditions are met.

5) Automatic Pre-Select

Support of manual control by automatic pre-select is an automatic function with pre-selection of parameters and their values, without manual control. In fact, automatic pre-select may be conceived as the replay of a set of pre-programmed actions. An example is automatic course control (auto-pilot control) on board ships; the navigator selects a new course, starts the course change manoeuvre by pressing a push-button, and the vessel will automatically alter course with a pre-selected turn rate. Note that pre-select automation can be superimposed upon the lower support levels (e.g., the navigator cannot execute manoeuvres with course changes of over 180 degrees).

6) Automatic Select

Support of manual control by automatic select is an automatic function that performs certain functions automatically. These functions can be selected or deselected (switched on or off) by the operator. An example is an automatic track keeper on a ship: The navigator selects navigation points (way points) to follow, enables automatic select mode by pressing a push-button, and the vessel will determine the optimal track between the two navigation points (considering the effect of water current, wind, and local weather by means of databases), and then start to follow this optimal track. The navigator only has to accept (correct, or reject) the proposed track.

7) Autonomous Manned Operation

During autonomous manned operation, the work is done automatically. The operator is still present on the vehicle, monitoring the system and surveilling the execution of the work procedure.

8) Autonomous Unmanned Operation

The work is done autonomously. There is no operator on the vehicle itself.

The effect of these levels of automation on the human factors of UMVs is roughly evaluated below. For this purpose, the effects of different levels of automation on the main human factors related issues were assessed by the author. Table 7-1 shows a summary of the results. In the Table, a + was rated when a positive effect on the related issue was expected, a ++ when the effect was rated very positively. A – was rated when a negative effect on the related issue was expected, a – when the effect was rated very negatively. The assessment is made subjectively by the author, based on the author's expertise in human factors and on the information derived from the literature. It has to be stressed that some items in the assessment are disputable, but the overall picture gives an indication of the advantages and drawbacks of the different automation levels. All the arguments that led to Table 7-1 are explained hereafter.

Table 7-1: Evaluation of the Application of Automation on Unmanned Military Vehicles (UMVs)

Automation Level	Human Factors Related Issues									System Output	
	Peripheralization: Cognitive Issues		Peripheralization: Control Issues			General Issues					
	Task Involvement 1.1 ¹⁾	Vigilance 1.2	Direct Control 2.1	Maintaining Skills 2.2	Maintaining Awareness 2.3	Few Mental Resources Required 3.1	Relief of Physical Workload 3.2	Comfort 3.3	Little Training Required 3.4	Output Quality	Economical Usage
1) No Automation	++	++	++	++	+	++	--	-	--	++	--
2) Manual Augmented	++	++	++	++	+	++	-	-	-	++	--
3) Manual Augmented Limited	++	++	+	++	+	++	-	-	-	++	-
4) Co-operative	+	++	-	+	-	++	+	+	+	+	+
5) Automatic Pre-Select	+	++	-	+	-	++	+	+	++	+	++
6) Automatic Select	-	++	-	-	-	++	+	+	++	+	++
7) Autonomous Manned	-	+	++	--	++	-	--	--	++	-	++
8) Autonomous Unmanned	-	-	++	--	++	--	++	+	--	-	++

Note: -- = very negative effect
 - = negative effect
 + = positive effect
 ++ = very positive effect

As indicated in Table 7-1, *task involvement (1.1)* – a low state increases the risk of complacency (i.e., a low index of suspicion due to automation) – is significant at lower levels of automation. The operator is (nearly) solely operating the UMV, directly controlling airframe and sensors. The operator is closely ‘in-the-loop’, that is, he is continuously involved in manual control activities, and, as well, continuously physically influenced by the behavior of the vehicle. The more automatic equipment is installed, the more the operator will rely on this, which increases the risk of complacency. In automation levels 6 – 9 there are situations that complete functions will be taken over by the machine, resulting in a low degree of task involvement (i.e., high risk of complacency).

Vigilance (1.2), defined as the ability to detect infrequent signals over prolonged periods of time, is high when the operator actively participates in the process. At automation levels 1 – 6 there are still a number of manual activities to perform by the operator. This is hardly the case during autonomous operation (levels 7 – 8), when nearly all operator functions are performed by the automated systems; however, the negative effect on vigilance will be limited in these situations when adequate feedback of the process state is provided to the operator.

In the lower levels of automation (levels 4 – 6) there is a direct link between operator control actions and process control activities. In case of high level automation (levels 7 – 8) there is a direct link between automatic system actions and process control activities. In both cases it is well possible to match input and output, which has a positive influence on *direct control (2.1)*. In semi-automated operation (levels 4 – 6), control activities are performed by operator and by machines simultaneously. It is then well possible that the sequencing of the output activities is conflicting; automatic functions will be executed more or less independently from actions taken by the operator (e.g., it is known that pre-select parameters may be changed during execution just to fool the automatic system in order to speed up the sequencing, or to start the sequence earlier). This has a negative influence on direct control.

Automation has a drawback on *maintaining skills (2.2)*, that is, the ability to perform the manual task properly when situations require switching back from automatic to manual control. Literature indicates that, the more automatic systems there are introduced, the more the operator will be placed out-of-the-loop. A lack of operator involvement is the result, with increasing risk in loss of skill. Particularly in the design of autonomous systems this deserves attention.

About *operator awareness (2.3)*, defined as the ability to perceive elements in the environment and to understand their meaning, it is stated that the operator is fully aware of machine state and controlled process state in case there is a high degree of direct control (see 2.1, the levels 1 – 3, and the levels 7 – 8), provided that there is adequate feedback of machine and process state. However, in levels 1 – 3 it may be expected that the operator is not fully aware of what the impact of his actions be on a number of activities (e.g., does his activity still fit in the work plan; what are the actual costs; are there time delays; are there changes in the work plan). Worst operator awareness is rated when a part of his activities is taken over by automated systems (i.e., items 4 – 6). Machine and operator are performing their assigned activities, with the risk that the machine performs activities that are not (or insufficiently) perceived by the operator/supervisor. For example, in case of an automatic visual target tracking system, it is important to have the system dead-reckoning when the target is obscured. Again, adequate feedback is essential in this case.

Part-task automation (levels 1 – 6) has a positive effect on the required *mental resources (3.1)* (i.e., routine tasks require few mental resources, resulting in low mental workload). The operator still directly perceives (e.g., by force feedback, auditory/vibration feedback) the system’s activities, and few mental transformations have to be made to understand what is going on, and what (manual) activities have to be performed. It is

assumed that more operator attention is required during autonomous operation, particularly in an unmanned situation. The operator is then tele-operating the system, while collecting information only through feedback systems. In that case it is expected that more mental transformations are needed (e.g., engine rpm has to be verified by means of an indicator on a screen, instead of interpreting engine noise/vibration).

Physical workload (3.2) – the biomechanical conditions of the operator during task execution is fully relieved during autonomous unmanned operation when the operator is located in a remote station. There will be some relief in case certain functions are taken over by automatons (levels 4 – 7); no relief of physical workload is expected when no automation is installed (level 1), or when the operator is manning an autonomous system (level 7). In the latter case, the operator is sitting on board a machine that performs activities autonomously, most of which the operator is not aware of or even may not expect.

Comfort (3.3), in the sense of physical workload, is rated low for low level of automation (levels 1 – 3), and medium for part-task automation (levels 4 – 6). Comfort, in the sense of being informed about the actual status of the total system, is rated very low in case of manned autonomous operation (level 7). The machine will perform actions that are not attended by the operator, who is sitting in the cabin.

Little training (3.4) is required in situations of part-task and full automation (i.e., automation levels 4 – 7). Note that training in autonomous unmanned operation (level 8) may include tasks that are not relevant in the context of the other automation levels (1 – 7).

System output quality is rated positive when few operator functions are automated. The more automatic systems are used, the less flexible the system will be. In case of part-task automation conflicts between operator actions and automatic system activities are likely to happen; in case of autonomous operation the sequencing, the function execution mostly is pre-programmed. In contrast to this, *economical usage* of the system will increase the more automatic systems are used (i.e., use on a continuous basis; fine-tuned in energy consumption for each job; better maintenance scheduling, less influence of environmental disturbances, etc.).

7.2.3 Recommendations

The following recommendations with respect to automation are given:

1) Select the proper level of automation

Each level of automation has its specific implications on the human factors aspects. When considering Table 7-1, a number of conclusions can be drawn. Low level of automation (levels 1 – 3) results in best quality of work and will not lead to operator peripheralization. However, the operator then performs under a high degree of physical load which limits the economical usage of the equipment. Medium level of automation (levels 4 – 6) is rated most positively. It is essential, however, that adequate feedback of the system state is provided to the operator so that optimal awareness is maintained (e.g., by providing visual display information and haptic feedback in the controls). The operator is kept in-the-loop which benefits the quality of task execution. Total (autonomous) operation is only beneficial in an unmanned configuration.

2) Keep the operator in-the-loop, increase operator awareness, and provide adequate feedback

The operator should actively participate in the job. Adequate visual feedback on displays should be presented for monitoring purposes, and haptic feedback by providing active controls for sensory information. Have the

operator activate sequences, or confirm the actual system status, on a regular basis. Avoid simultaneous monitoring and manual control activities. Avoid discrepancies between indicators and actual mode, e.g., use pushbuttons with visual indicators. Introduce dedicated displays, presenting the present status, the oncoming actions, and the current plan. The above mentioned importance of feedback is confirmed in the literature, including lessons learned in cockpit automation, and in generic model descriptions of a human-machine interface confirming the benefits of operator-in-the-loop performance [12]. Automation may result in eliminating or replacing critical cues. For example, specific information in manual control tasks (e.g., haptic information in joystick controls) is needed to detect system state changes [13]. Norman [14], as well as Korteling and Van Gent [15], stated that without appropriate feedback, operators are indeed out-of-the-loop: They may not be aware whether their input has been received, whether actions are performed properly, and what the intentions of the system are. In tracking tasks, error detection is better with manual control, due to the presence of proprioceptive feedback [16]. Kessel and Wickens [17] hypothesized that the fact that subjects operating under manual control had both visual and proprioceptive feedback, contributed to better performance. The need for appropriate feedback will increase with increasing complexity and with increasing autonomy of the system.

3) Introduce flexible automation

The operator should be able to select the automated activities at all time. This puts high demand on the designers of the automation algorithms. A good way to overcome this problem is to have the operator 'learn' the system how to perform the individual activities (e.g., the operator first shows the machine how to equalize a pile of material, or, how to put a load at certain positions when performing fork work activities).

4) Natural operation

The system should perform automatic activities as if this was done by the operator himself during automatic task execution. There will be less unattended actions of the system, which improves the operator's awareness and comfort, increasing total system safety and performance. Natural operation is particularly important when the operator has to override the automatic system by switching back to manual control.

5) Forestall loss of skill

The best way to prevent the loss of operator skill is probably to periodically give the operator dedicated training. Another possibility is to require the operator to perform skill critical tasks manually at certain times, even though the task may have been allocated to the automated system. Furthermore, the use of active controls, and the use of a system in which the operator 'learns' the machine how to perform a task will also help to prevent skill loss. Both these options were mentioned earlier.

6) Smooth mode transitions

Enable a smooth transition between manual and automated control mode, e.g., prevent sudden forces on controls. In fact, this implies that active controls must be installed. The operator continuously feels what the automatic system is doing just by putting his hands on the controls. Taking over manual control could then be just a matter of further activating that control (e.g., putting pressure on the grip, or activating a switch).

This Introduction outlined various human factors considerations in the use of automatic systems. It indicated possible advantages and disadvantages of the various levels of automation.

7.2.4 References

- [1] Parasuraman, R. and Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. Human Factors.
- [2] Stokes, A., Wickens, C.D. and Kite, K. (1990). Display technology, human factors concepts. Warrendale PA: Society of Automotive Engineers.
- [3] Boff, K. and Lincoln, J.E. (1988). Engineering Data Compendium: Human Perception and Performance. Wright Patterson AFB, OH: AAMRL.
- [4] Wiener, E.L. (1988). Cockpit automation. In: E.L. Wiener and D.C. Nagels (Eds.) Human factors in aviation (pp. 433-461). San Diego: Academic.
- [5] Satchell, P.M. (1993). Cockpit monitoring and alerting system. Brookfield: Ashgate.
- [6] AGARD (1986). Improved guidance and control automation at the man-machine interface. Hollister, W.M. (Ed.). AGARD advisory report AR-228. Neuilly-sur-Seine: NATO.
- [7] Wickens, C.D. (1992). Engineering Psychology and Human Performance. New York: Harper Collins.
- [8] Sheridan, T.B. (1988). The system perspective. In: Wiener, E.L. and Nagel, D.C. (Eds.) Human factors in aviation. San Diego: Academic Press.
- [9] Rasmussen, J. (1983). Skills, rules and knowledge; signals, signs, and symbols, and other distinctions in human performance models. IEEE Transactions on Systems, Man, and Cybernetics, 13, 257-266.
- [10] Hawkins, F.H. (1987). Human factors in flight. Brookfield: Gower Publishing Company.
- [11] AGARD (1984). Human factors considerations in high performance aircraft. AGARD conference proceedings CP-371. Neuilly-sur-Seine: NATO.
- [12] Passenier, P.O. and Van Delft, J.H. (1997). Human factors in process control: designing the human interface. Journal A, 37, 10-14.
- [13] Young, L.R.A. (1969). On adaptive manual control. Ergonomics, 12, 635-657.
- [14] Norman, D.A. (1989). The problem of automation: Inappropriate feedback and interaction not overautomation. ICS Report 8904. La Jolla, CA: University of California, San Diego, Institute for Cognitive Science.
- [15] Korteling, J. and Van Gent, R.N.H.W. (1994). Anticipatie en actieve stuurmiddelen bij helicopterbesturing [Anticipation and active controls in helicopter flight]. Report TM 1994 A-2. Soesterberg, The Netherlands: TNO Human Factors.
- [16] Parasuraman, R., Mouloua, M. and Molloy, R. (1996). Effects of adaptive task allocation on monitoring of automated systems. Human Factors, 38, 665-679.
- [17] Kessel, C.J. and Wickens, C.D. (1982). The transfer of failure detection skills between monitoring and controlling dynamic systems. Human Factors, 24, 49-60.

7.3 HUMAN AUTOMATION INTEGRATION WITH CONTRACTUAL AUTONOMY

7.3.1 Introduction

7.3.1.1 Function Allocation

Automation is continually improving in capability with associated changes in perceptions of appropriate human roles and the suitability of functions for human and/or machine performance. Traditional engineering mostly used the “left over” principle for allocation of function, where the technical system was designed to do as much as is feasible from an efficiency point of view, and the rest was left for the operator. HF engineering introduced the compensatory principle, where human and machine capabilities are compared on salient criteria and the function allocation is made so that the respective capabilities are used optimally. In 1951, Paul Fitts suggested some simple criteria for allocating functions between people and machines to predict roles in future air navigation and air traffic control systems [1]. Fitts distinguished between four kinds of control systems, namely:

- 1) Fully automatic control;
- 2) Automatic control with human monitoring;
- 3) Semi-automatic control supplemented by human performance of critical functions; and
- 4) Primary control by human operators.

The 1994 NATO RSG workshop on function allocation [2] reiterated the questions posed by Fitts and his colleagues which still lacked general answers:

- Should the human monitor the (technical) system given that humans are poor monitors?
- Should the (technical) system monitor the human?
- If so what roles should the human play and what are their responsibilities?
- Are humans included in systems just to deal with those functions that engineers can not automate?

Options on decision making were noted to range from the principle that the human should make all decisions, because humans are responsible for systems, to the principle that there are some decisions that humans should never be permitted to make.

In the 1980's, with increasingly capable intelligent computing, ideas of human-computer teamwork, cognitive engineering, cognitive automation and joint cognitive systems began to emerge [3]. According to the *complementarity* principle, function allocation serves to support and sustain human ability to perform efficiently. Here, the focus shifts from human-machine interaction to human-computer co-operation, and from the internal functions and structure of the human and machine to the external functions and establishing the system boundaries [4].

The capability for collaborative working with other agents, including humans, is a goal for intelligent automation. Taylor and Reising [5] noted that in order to work collaboratively with humans, intelligent automation probably requires a functional architecture with the following attributes:

- A model of human decision making and control abilities.

- The ability to monitor human performance and workload through behavioural and physiological indices.
- The ability to predict human expectations and intentions with reference to embedded knowledge of mission plans and goals.

7.3.1.2 Automation Reliability, Trust and Use

Issues of “trust” have featured strongly in implementation of ideas of dynamic function allocation, automated decision support and human-computer collaborative adaptive systems. This is in response to concerns about human monitoring of unreliable automation and the need for control strategies to mitigate bias from complacency and over-trust, or alternatively, under-trust and disuse [6].

Early UK MOD research with aircrew investigated the structure and measurement of trust to help design automation safeguards. A study of twin-crew RAF Tornado aircraft operations, elicited tactical decision making scenarios and aircrew rated them for the importance of factors associated with trust [7]. Demand for trust was associated with perceived risk and the probability of negative consequences, whereas the supply of trust was related to the requirement for judgement and awareness, and uncertainty and doubt in making decisions. Relying on others to make risky decisions calls for a large amount of trust. If the decision requires another person exercising a high degree of awareness and judgement, and there is much uncertainty and doubt in the decision provided, then the actual trust engendered by the decision will be low. In a follow-up study on the quality of aircrew teamwork [8], trust was found to be a significant factor in distinguishing between good and poor teamwork performance. Trust was rated at a significantly lower level in single-seat RAF Harrier operations (i.e., human-computer teamwork) than in two-seat RAF Tornado aircraft tactical operations (i.e., both human-computer and human-human teamwork).

Several models of trust have been proposed. Riley [9] developed a model of the relationships between trust, operator skill level, task complexity, workload and risk, self-confidence and automation reliability. Studies in which workload and reliability were varied, led to refinement of the model to include factors of fatigue and learning about system states [10]. Further research has modelled trust as a function of recent performance, and the presence and magnitude of fault, with subjective trust increasing with automation reliability [11]. The relationship between reliability and trust was confirmed by human monitoring performance measures indirectly measuring trust [12]. Recent work has extended modelling to investigate how the dynamics of trust and reliance depend on information sharing [13], and how trust becomes over-trust through unintended use [14].

Experimental evidence has verified that unexpected automation failure leads to a breakdown of trust, and to difficulty in the recovery of trust with a loss of faith in future teamwork performance. As trust declines, manual intervention increases [15,16]. Research has showed how when workload is increased, over-trust or complacency develops with automatic systems, and coupled with vigilance problems, this is likely to lead to failure to detect performance deviations and decrements in automation performance [17]. Operator detection of automation failure is substantially degraded with a static allocation fixed over a period of time, favouring dynamic adaptable allocation [18]. Manual task reallocation has been proposed as a countermeasure to monitoring inefficiency and complacency since short periods of intermittent manual task reallocation, or cycling between manual and automation control, reduces failures of monitoring [19]. By maintaining manual skill levels, and enhancing situational awareness, manual task re-allocation helps when intervention is needed following automation failure. However, without active involvement, it is difficult to maintain an appropriate dynamic internal model of the important changing relationships needed for regaining manual control following automation [20]. Experimental studies have shown that with competing demands for

attention, humans are poor at monitoring automation for occasional malfunctions, exhibiting automation complacency [17]. Humans also have poor awareness of adaptable automation failure [21,22].

Generally, trust is best considered as an *intervening variable* between automation reliability and automation use [6]. For purposes of measuring aiding effectiveness, like “confidence”, trust operates as a psychosocial attitude with inherently variable subjective complexity, rather than as a cognitive functional state such as “situation awareness” and “workload”. Trust is unlikely to be reliably linked to performance and effectiveness. Furthermore, “trust” is unlikely to provide reliable psychometric or concomitant behavioural measures (qualitative or quantitative), with useful sensitivity, discrimination, diagnosticity or predictive power.

7.3.1.3 Trustworthy Levels of Automation

For the design of adaptable automation and automated decision support, research effort is needed to be directed at constructing and constraining human-automation relationships, interactions and behaviours in a manner that naturally engender trust. Methods for delegating authority to automation are needed that manage and control risks of automation in a sensible, regulated and predictable manner, with appropriate safeguards. Safeguards are needed against breakdown or failure in performance to ensure that operator trust in system functioning is maintained at realistically appropriate levels, without adversely affecting situational awareness. The first Law of Adaptive Aiding states that “computers should take tasks, but not give them” [19]. Automatic reallocation of tasks to manual performance seems close to a violation of this law. In particular, variable assistance and allocation could lead to unacceptable unpredictability. So, awareness of the current task allocation strategy is an important factor for system effectiveness, but this may not be easily achieved by seamlessly adaptable aiding. Careful consideration is needed of the procedures for implementation of dynamic task allocation and re-allocation.

The building of trust between the operator and the computer automation system has been identified as a key issue in enabling the capability of cognitive automation. Trust is built when consistency and correctness is observed in the computer system’s decisions and actions. Two important guidelines for building trust have arisen [23]:

- *Define the Prime Directives.* These are overall governing rules which bound the behaviour of the aiding system, and yet provide a logical structure for aiding system to act in a rational and reliable manner, avoiding arbitrary behaviour, so that the human does not experience any surprises, e.g., Asimov’s Laws of Robotics.
- *Specify the Levels of Autonomy.* These also bound the behaviour of the aiding system by limiting its decision authority for the performance of specific sub-functions to a set of system configurations specified and set by the operator.

Trust is built on awareness of proven performance. Adaptive strategies for coping with control of complex, dynamic situations, such as automatic unburdening and manual re-allocation, will need careful adaptive logic to ensure their appropriateness. The design of the functional interface needs to ensure that appropriate levels of awareness of the current task allocation are easily maintained. Awareness is needed to avoid task contention, and to ensure that tasks are not overlooked or performed incorrectly.

Ideas of levels of automation have been proposed to represent scales of delegation of tasks to automation, with implications for reliability, use and trust. Sheridan and Verplanck [24] first proposed 10 possible levels of allocation of decision-making tasks between humans and computers. More recently, Parasuraman, Sheridan and Wickens [25] have considered the application of automation to a four-stage model of independent

information processing functions (information acquisition, analysis, and decision selection and action implementation). In doing so, they have sought to apply a revised set of levels of automation.

- The computer decides everything and acts autonomously, ignoring the human.
- The computer informs the human only if it, the computer, decides to.
- The computer informs the human only if asked.
- The computer executes automatically, then necessarily informs the human.
- The computer allows the human a restricted time before automatic execution.
- The computer executes the suggestion if the human approves.
- The computer suggests an alternative.
- The computer narrows the selection down to a few.
- The computer offers a complete set of decision alternatives.
- The computer offers no assistance. The human must make all the decisions and actions.

The term autonomy has been introduced to describe the bounding of functioning and decision authority of advanced automation and intelligent decision systems. Autonomy can be defined simply as the capability to make decisions. Thus, autonomy can be considered in terms of the freedom to make decisions, considering constraints on decision-making (limitations, boundaries, rules, regulations), decision-making abilities (authority, responsibility, competency), and the capability to make different kinds of decisions (classes, functions, levels).

In the 1980's, the DARPA/USAF Pilot's Associate (PA) program provided a practical implementation of intelligent pilot aiding based on prime directives and levels of autonomy (LOA). PA design was guided by a top-level operational philosophy based on the pilot being in charge. The goal of the PA was to provide consistently correct information, and to aid the pilot's decision making by helping to manage workload, reduce confusion, and simplify tasks. This led to the philosophy of the PA as an intelligent subordinate to the pilot, with specific capabilities for decisions and actions. These top level requirements led to specific operational relationships (ORs) for discrete PA sub-functions interactions, with increasing degrees of automation and autonomy. From these ORs, pilot selectable levels LOA were obtained for groups of functions governed by the required pilot operational relationship and interaction [26]. Five discrete LOA modes were proposed, namely: Inactive, Standby, Advisor, Assistant, Associate. Each LOA mode was associated with tailorable functional clusterings for flexible responding to avoid too rigid automation imposed by design. These modes were aimed to provide a bounded, communicable structure for delegated levels of authority, minimising mode confusion, and building trust and confidence. Generally, human factors research indicates that the required control structure should be cognitively simple, and not complex. Pilots tend to view computer autonomy simply as either automatic, with or without status feedback; semi-automatic, telling what will happen and asking permission to proceed; or advisory, providing information only.

7.3.2 Contractual Autonomy

7.3.2.1 Pilot Authorisation and Control of Tasks

In order to address the requirement for a practical implementation of LOA, under the UK MOD Cognitive Cockpit programme a framework was created for pilot interaction and delegation of adjustable levels of autonomy, known as the PACT system (Pilot Authorisation and Control of Tasks). PACT spans the range of

HUMAN AUTOMATION INTEGRATION

possible levels of allocation of decision making tasks, or levels of autonomy, between humans and computers [24,25]. The PACT framework is intended to provide trustworthiness in the information and behaviour of adaptable automation [27,28]. The PACT framework is summarised in Table 7-2.

Table 7-2: Bonner-Taylor PACT System

Primary Modes	Levels	Operational Relationship	Computer Autonomy	Pilot Authority	Adaptation	Information on performance
Automatic		Automatic	Full	Interrupt	Computer monitored by pilot	On/off Failure warnings Performance only if required.
Assisted	4	Direct Support	Advised action unless revoked	Revoking action	Computer backed up by pilot	Feedback on action. Alerts and warnings on failure of action.
	3	In Support	Advice, and if authorised, action	Acceptance of advice and authorising action	Pilot backed up by the computer	Feed-forward advice and feedback on action. Alerts and warnings on failure of authorised action.
	2	Advisory	Advice	Acceptance of advice	Pilot assisted by computer	Feed-forward advice
	1	At Call	Advice only if requested.	Full	Pilot, assisted by computer only when requested.	Feed-forward advice, only on request
Commanded		Under Command	None	Full	Pilot	None performance is transparent.

PACT simplifies the number of automation modes required – fully automatic, assisted, commanded – with a further secondary levels nested within the semi-automatic assisted mode, which can be changed adaptably or by pilot command. The PACT framework employs military terminology for categories of support in British Army land forces (Mike Bonner, personal communication). This provides realistic operational relationships compatible with military user control schemata. It is a logical, practical set of levels of automation, with progressive operator/pilot authority and computer autonomy supporting situation assessment, decision making and action, as illustrated in Figure 7-1.

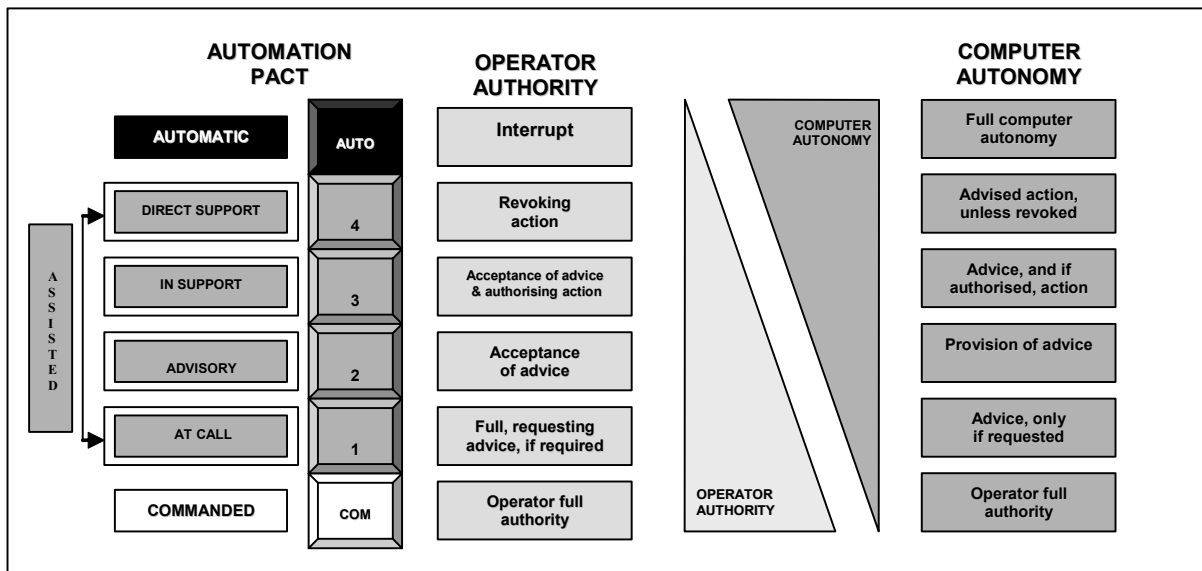


Figure 7-1: Pact Progression of Operator Authority and Computer Autonomy.

The purposes of the PACT framework can be summarised as follows:

- To bound the behaviour of the aiding system;
- To limit its decision authority to the performance of specific sub-functions; and
- To enable a set of system configurations to be specified, set and adjusted by the operator.

PACT is based on the idea of *contractual autonomy*. Using an aircrew term from co-operative air defence, the pilot forms a set of “contracts” with the automation by allocating tasks to PACT modes and levels of automation aiding. The contract defines the specific nature of the operational relationship between the pilot and the computer aiding for co-operative performance of specific sub-functions and tasks. In setting the PACT contract, the operator defines:

- What sub-functions and tasks are aided, when and how;
- What level of assistance is provided as primary or default, and when;
- What levels of assistance are permissible for anticipatable contingencies, and when;
- What are permissible triggers for changing levels of assistance, either contextual or by operator command; and
- What information is provided to the operator, when and how, including status advice, feed-forward/feedback course of action information and saliency.

Thus, autonomy is limited by the set of contracts made between the pilot and the computer automation system governing and bounding the performance of tasks to a set of sensible and predictable co-operative behaviours according to rules of operation (context, resources). Fighter pilots develop similar inter-personal contracts in planning control of multi-aircraft manoeuvres in co-operative air defence. The PACT autonomy contracts are binding delegation agreements for the computer. Only the pilot can set or modify the PACT contracts, or define a priori the contextual circumstances for real-time adaptation PACT changes. Mission functions and

HUMAN AUTOMATION INTEGRATION

tasks can be set to PACT levels by allocation individually or grouped in related scripts or plays, at different levels of abstraction, in a number of ways:

- Pre-set operator preferred defaults.
- Operator selection during pre-flight planning.
- Changed by the operator during in-flight re-planning, probably using Direct Voice Input commands.
- Automatically changed according to operator agreed, context-sensitive adaptive rules.

Figure 7-2 illustrates a set of mission functions and tasks with PACT contractual autonomy levels arranged along a timeline in a hypothetical task network. This provides the operator with implicit if not explicit control, so as to engender trust through understanding of automation functioning. Thus, the pilot retains authority and executive control, while delegating responsibility for the performance of tasks in a sensible and predictable manner to the computer.

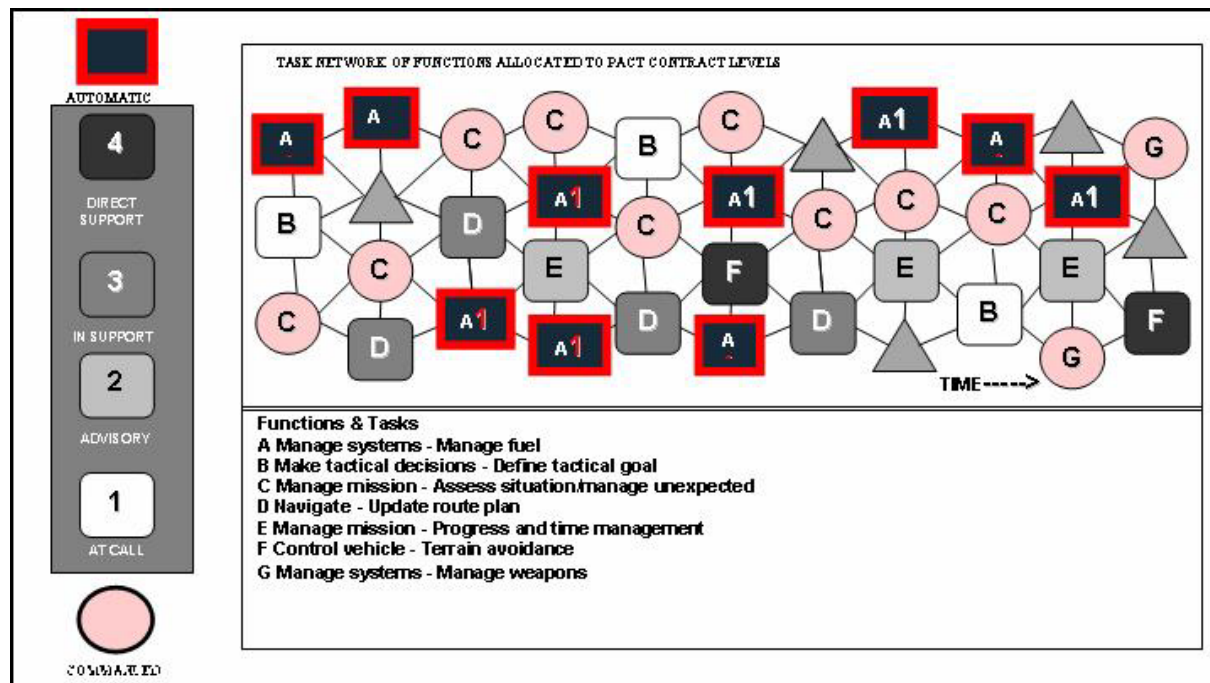


Figure 7-2: Task Network of Functions and Tasks Set to Pact Contract Levels.

In the Cognitive Cockpit implementation, the PACT system operates within an adaptive system architecture that couples on-line monitoring of the pilot's functional state and on-line task knowledge management and decision support for context-sensitive aiding, deriving information to mediate the timing, saliency and autonomy of the aiding. The PACT framework provides the necessary and sufficient levels of autonomy for the management of tasks. Three principle agents with different tasks comprise the Cognitive Cockpit system:

- A *Cognition Monitor* (COGMON) is responsible for monitoring the pilot's physiology and behaviour to provide an estimation of the pilot's functional state.
- A *Situation Assessor Support System* (SASS) is responsible for monitoring the aircraft situation and outside environment, generating advice and recommending courses of action.

- A *Task Interface Manager* (TIM) is responsible for monitoring the mission plan, deciding automation and managing the cockpit interface.

The TIM module provides on-line analysis of higher-order outputs from COGMON and SASS, and other aircraft systems. A central function for this system is maximisation of the goodness of fit between aircraft status, ‘pilot-state’ and tactical assessments provided by the SASS. These integrative functions enable this system to influence the prioritisation of tasks and, at a logical level, to determine the means by which pilot information is communicated through the TIM and the associated cockpit interfaces. Overall, this system allows pilots to manage their interaction with the cockpit automation, by context-sensitive control over the allocation of tasks to the automated systems.

The TIM functional architecture comprised modules for goal-plan tracking and for interface, timeline, automation and task management utilising a blackboard for goal-plan tracking information. Details of the TIM functional architecture are provided elsewhere [37,38]. The idea of a tasking interface exploits the lessons learnt from the US Army’s RPA program [39]. It arose from the need to be able to predict pilot expectations and intentions with reference to embedded knowledge of mission plans and goals. The aim was to provide an adaptive or “tasking” interface that allowed the operators/pilots to pose a task for automation in the same way that they would task another skilled crewmember. It afforded pilots the ability to retain executive control of tasks whilst delegating their execution to the automation. A tasking interface necessitated the development of a cockpit interface that allowed the pilot to change the level of automation in accordance with mission situation, pilot requirements and/or pilot capabilities. It was necessary that both the pilot and the system operated from a shared task model, affording communication of tasking instructions in the form of desired goals, tasks, partial plans or constraints that were in accord with the task structures defined in the shared task model.

Providing flexible or adjustable levels of autonomy for the performance of tasks and functions is a key requirement for implementation of the tasking interface concept. Allowing pilots to choose various levels of interaction for the tasks they are required to conduct can mitigate the problem of unpredictability of automation. TIM utilises the monitoring and analysis of the mission tasks provided by the SASS combined with the pilot state monitoring of the COGMON to afford adaptation of automation, adaptable information presentation and task and timeline management.

In the Cognitive Cockpit implementation, PACT levels are triggered adaptively, in accordance with PACT contracts, in response to contextual input from COGMON, SASS and TIM mission goal-plan tracking (GPT). The intention is to monitor and manage the variability in performance through a barrier system approach (monitor, detect, correct, reflect performance), and through appropriate cognitive streaming interventions (join, break, divert cognition). TIM feedback and feed-forward control messages are used with appropriate multi-modal intervention saliency (background, hinting, influencing, directing, compelling) developed to reduce cognitive bias with decision support systems. All the tasks in the mission scenario are pre-allocated to *possible* PACT level contracts by the pilot. The individual task PACT levels (defaults and contingencies) are set to mitigate the risks to achievement of the individual task goals. The TIM Task Manager distinguishes between pending, active and completed tasks for the current scenario/vignette. Individual tasks progressed from pending, to active, and then to completed, as the scenario progressed.

7.3.2.2 PACT Evaluation

The operation of the PACT framework was successfully demonstrated to the MOD Cognitive Cockpit customer in 2001. It has subsequently been incorporated into interfaces for UAV control and been demonstrated

Analysis has provided additional sources of evaluation information. A risk analysis [40] indicated that generic risks of automation are likely to be mitigated by the Assisted PACT levels, as follows:

- The PACT system is designed to support the pilot's cognitive work. The support ranges from providing advice to providing action. The resultant cognitive work can be represented in terms of a Skills, Rules, Knowledge (SRK) perception-assessment-targeting-execution cognitive decision ladder using state flow transition diagrams. Control task analysis [41,42] has been used to identify the structure of the cognitive work performed by the pilot and by automation at each PACT level [43]. Figure 7-3 illustrates the control task analysis for PACT Level 3 Assisted-In Support, represented in decision ladder flow terms.

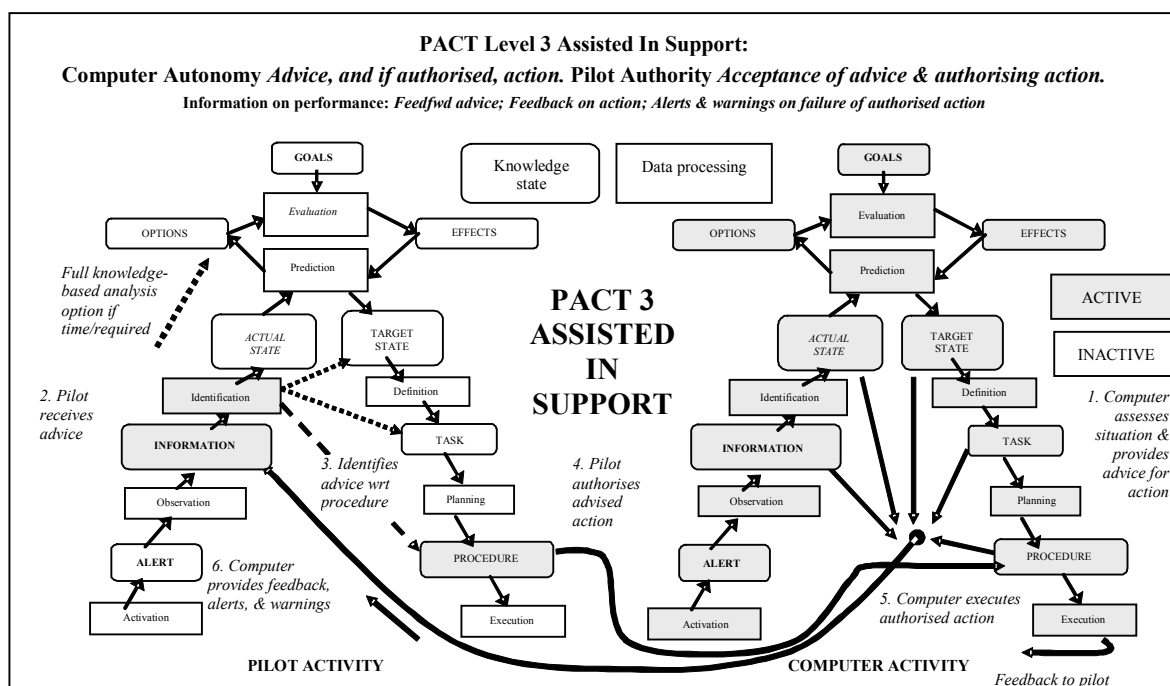


Figure 7-3: Control Task Analysis for PACT Level 3 Assisted In Support.

Figure 7-4 summarizes the levels of cognitive work estimated in four decision ladder phases (Perception, Assessment, Decision and Action (PADA)). Workload estimates were provided for PACT levels with immediate acceptance, critical acceptance and independent analysis. The analysis indicated that immediate acceptance of advice, associated with high levels of automation trust, was more likely to occur for Perception,

Assessment and Decision phases (i.e., situation assessment, status, goals, options, effects and plans) – but immediate authorisation of action was unlikely to occur, without critical appraisal, indicating a basic lack of trust. This may limit the reduction in cognitive load arising from automation of advised action (Direct Support). Concern about the validity of automated action is understandable during early familiarisation and confidence building. Critical appraisal of recommended courses of action probably will continue until the trustworthiness of the system can be established.

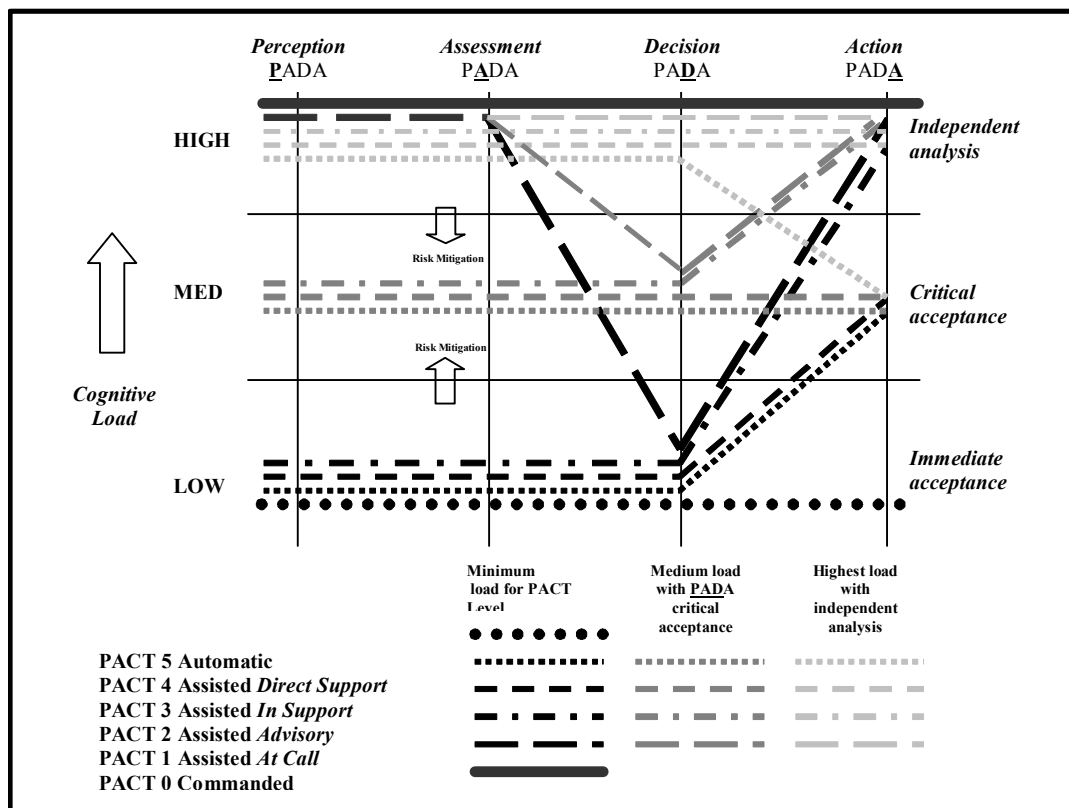


Figure 7-4: Cognitive Load Estimates for PACT Levels.

Some support for this observation on the untrustworthiness of action automation has been reported in an investigation of multiple UAV control. Ruff et al, [44] describe a study to assess the effects of automation reliability and levels of automation (LOA) on supervisory control of multiple UAVs. The LOA used were Management-by-Consent (MBC) and Management-by-Exception (MBE). These LOA equate to PACT Levels 3 and 4 respectively. Under MBC, the operator had to explicitly agree to suggested actions before they occurred. Under MBE, the system automatically implemented suggested actions after a pre-set time unless the operator objected. Results of two experiments showed that participants reported higher workload and difficulty with MBE. Under MBE conditions, time limits were set on manual intervention before automatic performance of the tasks (re-plans, image prosecution). This manipulation of reliability meant that erroneous action could occur. Participants generally chose to complete the tasks manually before MBE automatic action, indicating a lack confidence or trust in the system reliability.

7.3.3 Supervisory Control with Adjustable Autonomy

It seems likely that future manned and uninhabited platforms are both likely to have on-board cognitive automation operating with relatively high levels of autonomy or decision authority. Context sensitive technologies or “intelligent” computer software agents (e.g., Bayesian nets) offer the possibility of being able to control, regulate, direct and adapt system behaviour, within constraint boundaries, even in uncertain, novel, and unpredictable situations. The aspiration is to achieve the requisite cognitive agility, precision, reliability and safety of operations with intelligent systems, with the minimum human supervision and human-computer communication.

The PACT system has been applied in research on the management of multiple UAVs from manned cockpits, to help reduce pilot cognitive workload. It is seen as equally applicable to control of multiple UAVs from ground stations. Furthermore, PACT seems particularly relevant when coupled with intelligent organisation principles, control architectures and tools for structuring and delegating tasking co-ordination and execution workload [29]. DARPA sponsored work on air vehicles (AV) indicates value in similar autonomy solutions. The DARPA UCAV Advanced Cognition Aids Integration project for target engagement and multiple AV identifies four levels of autonomy, namely automate, exception (informs immediate action, OK or revoke), consent (authorisation required), manual [45]. The DARPA ICAV Intelligent Control of Unmanned AV project on mixed initiative distributed intelligence architecture for UAV operations identifies four levels of authorisation, namely autonomous, veto (proposal implicitly accepted after time out), permissive (proposal implicitly rejected after time out), manual [46]. For future envisioned UCAV operations, involving real-time, multiple (group) collaborating autonomous vehicles in joint operations with manned platforms, it seems likely that autonomous control levels will need extending beyond human command and computer support, to cover classes of autonomous complimentary, co-ordinated and co-operative planning and interactions.

Autonomy issues and implementation solutions have been addressed in work on multi-agent intelligent systems for problem solving in complex dynamic environments [34]. Mixed-initiative systems, dynamic adaptive autonomy and adjustable autonomy have been proposed to enable multi-agent systems to perform effectively with adaptability and flexibility. In the context of single-agent to human-user interaction, autonomy has generally been viewed as freedom from human influence – but for multi-agent systems, where the human user may be remote from operations, autonomy becomes a matter of the agent’s self-direction and goals, and the capability to dynamically form, modify or dissolve the agent organisation into goal-oriented, problem-solving groups. The degree of autonomy is considered to be implicit or explicitly linked to individual goals, and focuses on the decision making process used to determine how a goal is pursued free from intervention, oversight, or control by another agent (technical or human). Autonomy with respect to goals can be considered to be on a variable scale:

- Consensus or distributed control through consensus (working as a team member, sharing decision-making control equally with all other decision-making agents, all with equal authority);
- Master control (makes decisions alone, may communicate or give orders to other agents with authority);
- Locally autonomous (makes decisions alone, only agent with authority); and
- Command-driven or centralised control (makes no decisions about how to pursue goals, has authority, but must obey orders given by another agent).

Taylor [32,33] adds these agent autonomy levels to the PACT levels with a summary of the responsibilities in cognitive control model terms of advising and performing targeting (or governing), monitoring (or directing),

regulating and controlling (or operating) (Table 7-3). This enables consideration of the flow and transitioning of control in functional context rather than in terms of internal decision-making processes. Further exploitation of the PACT framework can be suggested as follows:

- Assign functions to multi-agent resources in CCII. Use PACT levels to define operational relationships.
- Assign a broad range of inactive reserve functions and operational relationships to PACT Level 1 Assisted At Call, i.e., pre-set at PACT Levels 2, 3, 4.
- Use PACT to define multi-agent support inter-relationships at the Master Control autonomy level.
- Use PACT agents to organise and filter prioritised information in Command and Control Information Infrastructure (CCII) for command intent and SA.

Table 7-3: Adjustable Autonomy Levels for Intelligent Multi-Agent Systems

AUTONOMY	TARGETING (GOVERNING)	MONITORING (DIRECTING)	REGULATING	CONTROLLING (OPERATING)
Consensus Autonomy	Multiple intelligent computer agents	Multiple intelligent computer agents	Multiple intelligent computer agents	Multiple intelligent computer agents
Master Autonomy	Intelligent computer agent	Intelligent computer agent	Intelligent computer agent + Authorised support agents	Intelligent computer agent + Authorised support agents
Local Autonomy	Intelligent computer agent	Intelligent computer agent	Intelligent computer agent	Intelligent computer agent
Automatic/ Commanded Autonomy	Operator	Computer agent performing some interpretation & planning + Operator interrupt	Computer agent performing recognition & scheduling + Operator interrupt	Computer/intelligent agent performing detection & execution agent + Operator interrupt
Assisted Direct Support	Operator	Operator authorising + Computer agent performing some interpretation & planning	Operator authorising + Computer agent performing recognition, & scheduling	Operator authorising + Computer agent performing detection & execution
Assisted In Support	Operator	Operator performing + Optional computer agent advising & performing some interpretation & planning	Operator performing + Optional computer agent advising & performing recognition & scheduling	Operator performing + Optional computer agent advising & performing detection & execution
Assisted Advisory	Operator	Operator performing + Computer agent advising interpretation & planning	Operator performing + Computer agent advising recognition & scheduling	Operator performing + Computer agent advising detection & execution
Assisted At Call	Operator	Operator + Optional computer agent	Operator + Optional computer agent	Operator + Optional computer agent
Command	Operator	Operator	Operator	Operator

Adjustable autonomy gives the agent architecture the ability to adapt their problem-solving to situations particularly in domains with unreliable communications and the possibility of agent failure, high degrees of uncertainty and resource contention needing distribution of tasks and co-ordinated planning to resolve conflicts. Distributed problem solving structures are generally thought to perform faster for complex tasks, when operating under uncertainty and changes in the environment, when few resources are shared, and when communication is unreliable. Centralised structures perform faster for simple tasks, when many resources are shared, when communication is reliable, and when there is no requirement to negotiate. Autonomy level agreements and communication protocols, joint intentions, and employing conventions for explicit commitment to specific interaction styles are considered necessary to establish reliability and trust. A central problem in adjustable autonomy is the determination of whether and when transfers of control to the operator/user should occur [47]. The transfer of control from agent to human is believed to require a balancing of the costs of interrupting a human user with the benefits for highest quality decision making when the human has

superior decision-making expertise. One technique proposes that transfer should occur when the expected utility of transfer is greater than that of retaining the decision-making. Another forces the agent to relinquish and transfer control if the uncertainty is high. Others transfer if any incorrectness in the agents decision can cause significant harm, if the agent lacks decision-making capability, or on the basis of thresholds of learnt rules. In multi-agent applications, cognitive strategies are needed for reasoning with adjustable autonomy in the operating context (situated autonomy) to provide the correct co-ordination, reordering and scheduling and to balance the costs, benefits, uncertainty and implications within the multi-agent group [48].

There is considerable potential for read-across for control architectures from cognition and joint cognitive systems for the control of distributed multi-agent systems. They use decision resources efficiency and enable the decision agility and adaptiveness needed for the manoeuvrist approach to military problem-solving. The use of cognitive control models will increase the transparency of control architectures and control authority for human user appreciation of the planning and interaction situation during collaborative problem-solving.

7.3.4 Conclusions

The PACT framework developed for pilot authorisation of control of tasks provides a simplified, practical set of adjustable levels of contractual autonomy capable of engendering trust in automation. An illustration of the idea of PACT as an enabling framework between and automation trust, reliability and use is shown in Figure 7-5. PACT enables the pilot to delegate responsibility for tasks to the computer through a set of contracts that limit autonomy and bound the behaviour of the aiding system, while maintaining the pilot's authority through executive control. Control task analysis, cognitive loading and risk analysis provide useful tools for understanding and modelling the functioning of the PACT system. The PACT framework seems sufficiently robust and useful to be applicable to other systems and environments requiring cognitive control with trustworthy variable levels of autonomy, such as the control of multiple uninhabited vehicles.

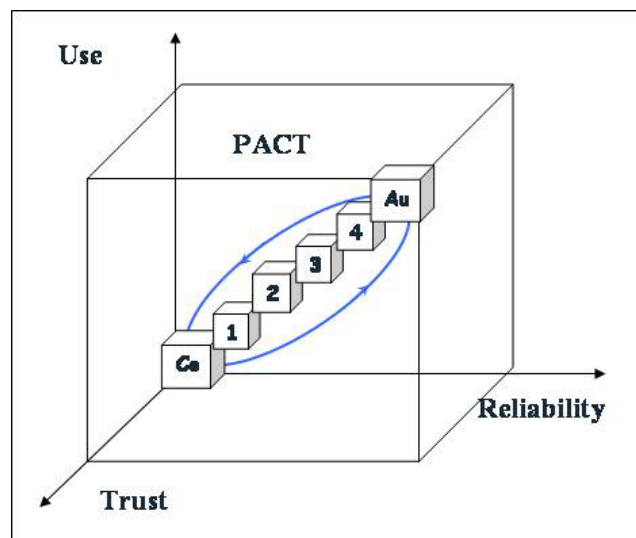


Figure 7-5: PACT Enabling Automation Reliability, Trust and Use.

A number of fundamental questions and key issues can be identified concerning the role of humans in advanced automated and intelligent systems. In particular, there is uncertainty over how to optimise the use of

human and computer decision resources, while preserving a human-centric system. These matters need to be understood in the context of the changing capability requirement responding to new military problem-solving challenges. Important changes are being made in the way in which military force is to be used in the future with the introduction of effects-based approach to the planning and conduct of joint operations. This will be enabled by network CCII, and will provide shared planning and situation appreciation, command intent and Combat Identification. The prime reason for human involvement in military decision-making with automated systems – human control of use of military force for safety assurance – seems established in military law and it is axiomatic for military relevance. Human knowledge, experience and judgement provide unique capability to analyse safety risks and to think ahead in uncertain and novel situations. The challenge is to provide information and decision systems that protect and preserve the human user's key role, and that augment and enhance the user's cognition rather than replaces the user in complex decision making. Recent developments in theory of cognition provide pragmatic approaches that are likely to improve understanding of the human factors issues, problems and solutions of human-computer collaboration. In addition, new approaches to the use of automation propose adjustable levels of computer autonomy with a strong socio-technical and cognition basis. These seem likely to provide sensible architectures for distributed, multi-agent intelligent systems that can be more readily appreciated by human users than traditional automation approaches.

7.3.5 References

- [1] Fitts, P.M. (1951). Human Engineering for an Effective Air Navigation and Traffic Control System. Washington, DC. National Research Council.
- [2] Beevis, D., Essens, P. and Schuffel, H. (1996). (Eds) Improving Function Allocation for Integrated Systems Design. CSERIAC SOAR 96-01. Crew Systems Ergonomics and Analysis Centre, Wright-Patterson Air Force Base, Ohio.
- [3] Hollnagel, E. and Woods, D.D. (1983). Cognitive Systems Engineering: New Wine in Old Bottles. International Journal of Man-Machine Studies, Vol. 18, pp. 583-600.
- [4] Hollnagel, E. (1997). Control Versus Dependence: Striking the Balance in Function Allocation. In: M.J. Smith, G. Salvendy, and R.J. Koubek (Eds), Design of Computing Systems. Advances in Human Factors/Ergonomics, 21B, pp. 243-246. Amsterdam: Elsevier.
- [5] Taylor, R.M. and Reising, J.M. (1998). The Human-Electronic Crew: Human Computer Collaborative Teamworking. In: Collaborative Crew Performance in Complex Operational Systems. Papers presented at the RTO Human Factors and Medicine Panel (HFM) Symposium held in Edinburgh, United Kingdom, 20-22 April 1998. NATO RTO-MP-4, AC/323(HFM)TP/2, ISBN 92-837-1008-8. Paper 22, pp. 1-17. NATO Research and Technology Organisation, Neuilly-sur-Seine Cedex, December 1998.
- [6] Parasuraman, R. and Byrne, E. (2003). Automation and Human Performance in Aviation. In: P.S. Tsang and M.A. Vidulich (Eds). Principles and Practice of Aviation Psychology, Chapter 9, pp. 311-356. Mahwah, NJ: Erlbaum.
- [7] Taylor, R.M. (1988). Trust and awareness in human electronic crew teamwork. In: "The Human-Electronic Crew: Can They Work Together? WRDC-TR-89-7008, Wright-Patterson AFB, OH.
- [8] Taylor, R.M. and Selcon, S.J. (1993). Operator and automation capability analysis: Picking the right team. AGARD-CP-520, Paper 20, NATO Research and Technology Organisation, Neuilly-sur-Seine Cedex.

- [9] Riley, V. (1992). Modelling the dynamics of pilot interaction with an electronic crew. In: *The Human Electronic Crew: Is the Team Maturing*. WL-TR-92-3078. Wright Patterson AFB, OH. July, pp. 103-107.
- [10] Riley, V. (1994). A theory of operator reliance on automation. In: M. Mouloua and R Parasuraman (Eds). *Human Performance in Automated Systems: Current Research and Trends*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- [11] Lee, J.D. and Moray, N. (1992). Trust, control strategies and allocation of function in human machine systems. *Ergonomics*, Vol. 35, pp. 1243-1270.
- [12] May, P., Molloy, R. and Parasuraman, R. (1993). Effects of automation reliability and failure rate on monitoring performance in a multi-task environment. *Proceedings of the 37th Annual Meeting of the Human Factors and Ergonomics Society*, Seattle, WA.
- [13] Gao, J. and Lee, J.D. (2004). Information sharing, trust and reliance – A dynamic model of multi-operator multi-automation interaction. In: D.A. Vincente, M. Moustapha and P.A. Hancock (Eds). *HPSAA II, Vol. II, Human Performance, Situation Awareness and Automation: Current Research Trends*, pp. 34-39, Mahwah, NJ: Erlbaum.
- [14] Itoh, M., Inahashi, H. and Tanaka, K. (2004). Overtrust due to unintended use of automation. In: D.A. Vincente, M. Moustapha and P.A. Hancock (Eds). *HPSAA II, Vol. II, Human Performance, Situation Awareness and Automation: Current Research Trends*, pp. 11-16, Mahwah, NJ: Erlbaum.
- [15] Muir, B.M. (1987). Trust between humans and machines and the design of decision aids, *International Journal of Man-Machine Studies*, Vol. 7, pp. 527-539.
- [16] Lerch, F. and Prietula, M. (1989). How do we trust machine advice? In: G. Salvendy and M. Smith (Eds). *Designing and Using Human Computer Interfaces and Knowledge-based Systems*. Amsterdam, Elsevier.
- [17] Parasuraman, R., Molloy, R. and Singh, I. (1993a). Performance consequences of automation induced complacency. *International Journal of Aviation Psychology*, Vol. 3, (1), 1-23.
- [18] Parasuraman, R., Mouloua, M., Molloy, R. and Hillburn, B. (1993b). Adaptive function allocation reduces the cost of static automation, *Proceedings of 7th International Symposium on Aviation Psychology*, Ohio State University, Vol. 1, pp. 178-181.
- [19] Rouse, W.B. (1994). Twenty years of adaptive aiding: Origins of the concept and lessons learnt. In: M. Mouloua and R Parasuraman (Eds.). *Human Performance in Automated Systems: Current Research and Trends*, pp. 28-33. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- [20] Carmody, M.A. and Gluckman, J.P. (1993). Task specific effects of automation and automation failure on performance, workload and situation awareness. *Proceedings of 7th International Symposium on Aviation Psychology*, Ohio State University, Vol. 1, pp. 167-171.
- [21] Taylor, R.M. and Shadrake, R. and Haugh, J. (1995). Trust and adaptation failure: An experimental study of uncooperation awareness. In: *The Human Electronic Crew: Can We Trust the Team?* *Proceedings of the 3rd International Workshop on Human-Computer Teamwork*. WL-TR-96-3039. Wright-Patterson AFB, OH, December 1995. DRA CHS Report DRA/CHS/HS3/TR95001/02, January 1995, pp. 93-98.

- [22] Taylor, R.M., Shadrake, R., Haugh, J. and Bunting, A. (1996). Situational awareness, trust and compatibility: Using cognitive mapping techniques to investigate the relationships between important cognitive system variables. In: Situation Awareness: Limitations and Enhancement in the Aviation Environment, Proceedings of AGARD AMP Symposium, Brussels, Belgium, 24-27 April 1995. AGARD-CP-575, pp. 6-1 to 14. NATO, Neuilly-sur-Seine Cedex.
- [23] Reising, J.M. (1995). Must the Human-Electronic Crew Pass the Turing Test? In: The Human Electronic Crew: Can We Trust the Team? WL-TR-96-3039, pp.103-108. Wright Patterson AFB, OH, December 1995. Proceedings of the 3rd International Workshop on Human-Computer Teamwork. DRA CHS Report DRA/CHS/HS3/TR95001/02, January 1995.
- [24] Sheridan, T.B. and Verplank, W.L. (1978). Human and computer control of undersea teleoperators. Technical Report. MIT Man-machine Systems Laboratory, Cambridge, MA.
- [25] Parasuraman, R., Sheridan, T.B. and Wickens, C.D. (2000). A model for types and levels of human interaction with automation. IEEE Transactions on Systems, Man, and Cybernetics. Part A: Systems and Humans, Vol. 30, No. 3, pp. 286-297, May 2000.
- [26] Krobusek, R.D., Boys, R.M., and Palko, K.D. (1989). Levels of autonomy in a tactical electronic crewmember. WRDC-TR-89-7008, Wright Patterson AFB, OH.
- [27] Taylor, R.M. (2001a). Cognitive Cockpit Systems Engineering: Pilot Authorisation and Control of Tasks. In: R. Onken (Ed), CSAPC'01. Proceedings of the 8th Conferences on Cognitive Sciences Approaches to process Control, Neubiberg, Germany, September 2001. University of the German Armed Forces, Neubiberg, Germany.
- [28] Taylor, R.M., Abdi, S., Dru-Drury, R. and Bonner, M.C. (2001). 'Cognitive cockpit systems: information requirements analysis for pilot control of cockpit automation'. In: D. Harris (Ed), Engineering psychology and cognitive ergonomics, Vol. 5, Aerospace and transportation systems, Ch. 10, pp. 81-88. Aldershot: Ashgate.
- [29] White, A.D. (2002). The human-machine partnership in UCAV operations. In: Proceedings of 17th Bristol UAV Systems Conference, 10-13 April 2002.
- [30] Taylor, R.M., Brown, L. and Dickson, B. (2002). From safety net to augmented cognition: Using flexible autonomy levels for on-line cognitive assistance and automation. RTO-MP-086 AC/323(HFM-085)TP/42. ISBN 92-837-0028-7. Paper No 27, NATO RTO Human Factors and Medicine Panel, Symposium on Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures, La Coruna, Spain, 15-17 April 2002.
- [31] Waters, M. and Taylor, R.M. (2004). A Bayesian Agent Approach to Autonomous Decision Making for an Unattended Cognitive Underwater Vehicle (UCUV). In: Proceedings of the Workshop on Uninhabited Military Vehicles (UMVs) – Human Factors of Augmenting the Force, RWS-010-P4, held in Leiden, The Netherlands, 10-13 June 2003. NATO RTO Human Factors and Medical Panel 078/Task Group 017, NATO RTO Neuilly-sur-Seine.
- [32] Taylor, R.M. (2002). Capability, Cognition and Autonomy. In: Proceedings of the NATO RTO Human Factors and Medicine Panel Symposium, HFM-084/SY-009, "The Role of Humans in Intelligent and Automated Systems", Warsaw, Poland, 7-9 October 2002. NATO, RTO, Neuilly-sur-Seine Cedex.

- [33] Taylor, R.M. (2003). Cognition and Autonomy in Distributed Intelligent Systems. In: D. Harris, V. Duffy, M. Smith and C. Stephanidis (Eds). *Human Centred Computing: Cognitive, Social and Ergonomic Aspects*. Vol. 3, pp. 330-334, Lawrence Erlbaum Associates, Mahwah, New Jersey.
- [34] Barber, K., Goel, A. and Martin, C. (2000). Dynamic Adaptive Autonomy for Multi-agent Systems. *Journal of Experimental and Theoretical Artificial Intelligence*. Vol. 12, Part 2, pp. 129-148.
- [35] Hollnagel, E. (2002). Cognition as Control: A Pragmatic Approach to the Modelling of Joint Cognitive Systems. Special Issue of IEEE Transactions on Systems, Man and Cybernetics A: Systems and Humans – “Model-Based Cognitive Engineering in Complex Systems” (In Press) <http://www.ida.liu.se/~eriho/>
- [36] Diethe, T.R., Dickson, B.T., Schmorow, D. and Raley, C. (2004). Toward an augmented cockpit. In: D.A. Vincente, M. Moustapha and P.A. Hancock (Eds). *HPSAA II, Vol. II, Human Performance, Situation Awareness and Automation: Current Research Trends*, pp. 65-69, Mahwah, NJ: Erlbaum.
- [37] Bonner, M., Taylor, R.M. and Miller, C. (2000). Tasking interface manager: Affording pilot control of adaptive automation and aiding. In: P.T. McCabe, M.A. Hanson and S.A. Robertson (Eds.), *Contemporary Ergonomics 2000*, pp. 70-74, London: Taylor and Francis.
- [38] Taylor, R.M. (2001a). Cognitive Cockpit Systems Engineering: Pilot Authorisation and Control of Tasks. In: R. Onken (Ed), *CSAPC'01. Proceedings of the 8th Conferences on Cognitive Sciences Approaches to process Control*, Neubiberg, Germany, September 2001. University of the German Armed Forces, Neubiberg, Germany.
- [39] Miller, C.A., Guerlain, S. and Hannen, M. (1999). The Rotorcraft Pilot's Associate Cockpit Information Manager: Acceptable behaviour from a new crew member. *Proceedings of the American Helicopter Society, 55th Annual Forum*, Montreal, Quebec, May 25-27, 1999.
- [40] Taylor, R.M. (2001b). Cognitive Cockpit Control Task Analysis. DERA Memo, DERA/CHS3/6.3/14/7, 7 March 2001.
- [41] Sanderson, P., Naikar, N., Lintern, G. and Goss, S. (1999). Use of cognitive work analysis across the system life cycle: From requirements to decommissioning. *Proceedings of the Human Factors Society 43rd Annual Meeting*, Houston, TX, pp. 318-322, Santa Monica, HFES.
- [42] Vincente, K.J. (1999). *Cognitive Work Analysis: Towards Safe, Productive and Healthy Computer-based Work*. New Jersey: Lawrence Erlbaum.
- [43] Taylor, R.M. (2001c). Cognitive Cockpit Risk Analysis. DERA Memo, DERA/CHS3/6.3/14/7, 26 February 2001.
- [44] Ruff, H.A., Calhoun, G.L., Draper, M.H., Fontejon, J.V. and Guilfoos, B.J. (2004). Exploring automation issues in supervisory control of multiple UAVs. In: D.A. Vincente, M. Moustapha and P.A. Hancock (Eds). *HPSAA II, Vol. II, Human Performance, Situation Awareness and Automation: Current Research Trends*, pp. 218-222, Mahwah, NJ: Erlbaum.
- [45] Leahy, M. (2001). DARPA UCAV Advanced Cognition Aids Integration. Paper presented to Unmanned Systems 2001. The 28th Annual Technical Symposium of the Association of Unmanned Vehicles International, Baltimore, July 2001.

- [46] Elmore, W. (2001). DARPA ICAV Intelligent Control of Unmanned Air Vehicles, Paper presented to Unmanned Systems 2001. The 28th Annual Technical Symposium of the Association of Unmanned Vehicles International, Baltimore, July 2001.
- [47] Scerri, P., Pynadath, D.V. and Tambe, M. (2001). Adjustable Autonomy in Real World Multi-Agent Environments. In: Agents '01, Proceedings of the 5th International Conference on Autonomous Agents.
- [48] Hexmoor, H. (2000). A Cognitive Model of Situated Autonomy. In: Proceedings of PRICAI-2000. Workshop on Teams with Adjustable Autonomy, pp. 11-20.

7.4 ADAPTIVE AUTOMATION FOR ROBOTIC MILITARY SYSTEMS

7.4.1 Introduction

Future Combat Systems (FCS) is a US Army program that will transform the battlefield Future force structure; doctrine and tactics will change as new systems are introduced; possibly in ways that can not be anticipated. Units of Action (UA) are being designed to be flexible, reconfigurable components of FCS tailored to specific combat missions. One aspect of increased flexibility will be the introduction of numerous robotic systems. The term robot is used in a generic sense to describe systems that are unmanned with some degree of autonomy that include aerial, ground, subterranean, naval surface and sub-surface vehicles. These systems will be an essential part of the future force because they extend manned capabilities, are force multipliers and most important, they can save lives.

Any major change in current doctrine implies problems as well as solutions. Robotic systems with diverse roles, tasks and operating requirements are being designed to exploit future battle spaces. The role of the human operator is not well understood; however most of the contemplated systems will require either active human control or supervision with the possibility of intervention. In the most extreme case, soldiers will operate multiple systems while on the move and while under enemy fire. In all cases, the workload and stress will be variable and unpredictable – changing rapidly as a function of the military environment. The purpose of this chapter is to investigate technologies that unload the warfighter interacting with unmanned systems during multi-tasking missions. First, we will investigate automation technologies, specifically their positive and negative effects on human performance and situation awareness. Next, we will discuss adaptive and adaptable processes as methods that potentially overcome the disadvantages of preset automation. The last section will survey diverse physiological measures that can be used to trigger adaptive processes emphasizing the rapid development of these methods and their current limitations.

Future robotic systems are being designed to be used in all facets of the modern battlespace and be, to the degree possible, autonomous. This requires both rapid response capabilities and intelligence built into the system. However, ultimate responsibility for system outcomes always resides with the human and in practice; even highly automated systems usually have some degree of human supervisory control [1]. Particularly in combat, some oversight and the capability to override and control lethal systems will always be a human responsibility for the following reasons [2]:

- System safety;
- Change in the commander's goals;
- Implied meta-goals; and
- Fratricide.

However, automation is not an all or nothing phenomenon. Automation can vary in the degree to which a particular function that was previously carried out by a human operator is allocated to a machine agent. This is the concept of “level of automation” (LOA) as discussed by Sheridan [3]. However, automation can vary in other dimensions as well, for example in the stage of human information processing that the automation is applied, whether to stages such as information acquisition and analysis, or to stages such as decision making and response execution. Parasuraman, Sheridan and Wickens [4] developed a taxonomy of human automation control that is two dimensional. Figure 7-6 shows rows as degree of automation and columns as type of processing function addressed. The four processing functions of information acquisition, information analysis, decision making/action selection, and action implementation are similar to the Observe-Orient-Decide-Act or OODA loop in the parlance of military command and control. The taxonomy also captures the multiplicity of control options from fully automated to fully manual for each of these functions. The decision space is not only complex, but it implies that there is not a single solution to partitioning control. Specifically, as the type of task the operator performs changes the control logic may need to change as well. This is understating the problem because the taxonomy does not consider either other tasks the operator is performing or the overall workload and stress imposed by the current environment. A review of the human performance literature reinforces the notion that there is not a single solution to partitioning; human performance varies greatly depending on the operator task and the current environment [5,4].

Processing task- type of auto	Info acquisition	Info analysis	Action selection	Action implementation
Full auto				
Auto-human informed sometimes				
Auto-human Informed				
Auto-human veto time limit				
Auto executes only if human approves				
Auto suggests				
Auto narrows				
Auto shows all options				
Manual				

Figure 7-6: Human-Automation Taxonomy with Rows Representing Degree of Automation and Columns Processing Functions. (Adapted from [4]).

7.4.2 Human Performance Issues for Automated Systems

Numerous problems related to human performance in automated systems have been identified in the literature. One problem with automated systems is the operator’s trust and level of use of the automation. Parasuraman and Riley [5] compiled both research and real world examples of automation misuse, disuse and abuse. They showed that the human operator ignored important indicators, failed to use reliable systems, misused unreliable systems, or misunderstood the true state of the system. The paper catalogued various human deficiencies related to supervisory control and, most important; the review motivated a good deal of subsequent research.

In another review article, Mosier and Skitka [6] examined what they termed cases of automation bias. The operator tended to over rely on automated systems even in cases where appropriate operator intervention would have averted performance problems. They did not identify an automation bias per se, but rather identified a number of performance problems related to lowered vigilance, high workload, time stress and loss of situation awareness (SA). SA problems resulted from a combination of automation complexity and poor display design. The best example was the Three Mile Island accident wherein operators were misled by too many malfunction indicators that were unrelated to the underlying problem. Again, there did not seem to be a coherent theory explaining automation bias rather the authors identified multiple causes of over reliance. Other researchers found that while there were circumstances where humans over relied on automation, there were other equally important instances where they should have relied on automation and did not.

For example, an Army supported study investigated operator trust issues related to the Battlefield Combat Identification System (BCIS) [7]. In an experiment with college students, the simulated aid's target identification rate was varied from 60 – 90% accuracy and the participants' task was to affirm or override the target decisions. Overall the subjects were twice as likely to be wrong when they agreed with an erroneous aid decision ($p(\text{error/aid error}) = .27$) then when they made override errors for cases when the aid was correct ($p(\text{error/aid correct}) = .13$) supporting the automation bias hypothesis.

However, other research from the same authors indicated exactly the opposite bias- disuse of appropriate automation. In a study similar to the BCIS study, college students were given 200 trials in which they had to decide whether a target was present on the display or not [8]. After each trial, target advisories were given to the students purported to be from either an aid (automatic target recognition (ATR) device) or a "peer". Participants were told the relative accuracy rates for the aids ("peers") and their own decisions and then had to decide whether to base future decisions on their own performance or that of the automated advisory (or peer). Surprisingly, even when the aid made $\frac{1}{2}$ as many errors and the subjects reward depended on accuracy, 80% of the subjects chose to make their own decisions. Also, subjects trusted "peer" advisories more than the aid advisory with the same accuracy level. They rationalized their decisions in terms of self reliance. However, the most salient difference between this study and the BCIS study was that subjects were told the ATR- "peer" decision **after** they had made their own decision. Thus there was no workload advantage to using the aid advisory because the operator's decision was made before the aids results were known.

The results are important because a simple manipulation (the order in which decisions were required) caused an automation bias to shift to a self-reliance bias. The same results were repeated in subsequent experiments, but the self-reliance bias was mitigated if the test subject was informed the reason for the ATR errors and were given appropriate feedback during the initial trials [9]. Anecdotal data also indicated mistrust of aids in cases where there was a high false alarm rates: the "cry wolf" phenomenon [10]. In summary, humans are neither universally over reliant or under reliant on automated systems. The crucial factors seem to be workload, time stress, false alarm rate and decision order.

Automation reliability has the same contradictory effects on performance depending on the task, workload and type of errors the automated device makes. A number of experimenters found no effect of aid reliability on performance [7,11,12]. The most likely reason is the lack of calibration of the subjects. For example, in the Dzindolet et al. study each subject received only one reliability level (60%, 75% and 90%) and they were not given the feedback that may have allowed them to respond effectively. The literature suggests that humans have problems understanding probabilities and may need some form of intervention in order to perform efficiently [13,14]. Reliability level effects depend both on operator strategies and the type of error the aid manifests. Meyer [15] has shown that when automation reliability is such that malfunctions are almost always correctly indicated – that is, the automation makes few misses, then the operator has high *reliance* on the

automation. This is an effective strategy, but can result in a problem when the automation *does* miss, because of the complacency effect. On the other hand, if automation reliability is such that few false alarms are made, then the operator has high *compliance*: if an automated alarm sounds, then the operator tends to immediately comply with the alarm and tend to the situation. Reliance on automated aids permits the operator to attend to tasks other than the automated task until the alert is triggered thus improving multitask performance and not just the performance on the automated task.

Research using realistic unmanned aerial vehicle (UAV) operator tasks indicted that reliant behaviors are affected principally by the misses. In contrast, compliance errors were affected by the false alarm rate, but not affected by miss rate of the automated device. However, increasing the operator's workload and decreasing the aid's reliability level had adverse effects on both compliance and reliance errors [16].

The issue is complicated because performance depends on the type of processing task the operator performs and paradoxically high reliability can result in costs as well as benefits. Rovira, McGarry and Parasuraman [17] investigated automation of artillery targeting decisions. For their particular task, they found that reliable automation improved the surrogate commander's decision latency without sacrificing accuracy. However, particularly for decision tasks related to choosing a course of action, higher reliability hurt the operator's performance when the aids gave incorrect information. The surrogate commanders trusted 80% accurate aids more than the 60% ones in cases where they should have been more skeptical (i.e., when the aids gave them incorrect information). Apparently, the advisories from 'trusted' aids were not scrutinized as thoroughly as those from less reliable aids.

One interpretation of the previous results is to assume that reliable aids lulled the operator into a false sense of complacency. However, the complacency literature suggests that the results depend on other factors besides trust. A number of researchers had failed to show complacency effects, motivating Parasuraman, Molloy and Singh [11] to investigate possible reason for this in a multitask aviation environment. Their most important finding was that complacency did not occur for low workload (single task) conditions. For the high workload task, the operator became complacent (over relied) on the aid when the aid had a constant reliability level; however, when the reliability level varied over a block of trials the performance decrement was ameliorated. This suggests that complacency was not so much a matter of trust, but a strategy to deal with high workload. If an aid acted in a predictable manner (constant reliability) then the operators would commit their resources to other tasks in a high workload environment causing a performance decrement in the unmonitored automation task.

The forcing function in most of these studies was high workload. The operator basically traded off situation awareness for workload reduction by depending on aids even in cases when it was not beneficial to do so. This was not universally true, in some cases automation improved overall performance even when the automated task required intervention because the operator's residual cognitive capacity was allocated effectively among the set of tasks [18,19]. However, too often, the loss of situation awareness related to inefficient automation monitoring leads not only to performance decrements, but also to an increasingly impoverished understanding of the work environment which can over time result in catastrophic errors [20,6,5]. Because of the uncertainty and risk associated with military environments, automating any but the most trivial tasks must be done with extreme caution. The soldier and his command chain need to maintain situation awareness; keeping the soldiers out of the loop will not only have consequences for the immediate task, but also predispose them to miss important cues signaling change [20]. Conversely, requiring soldiers to engage in multiple tasks could very well have the same consequences.

7.4.2.1 Adaptive Principles

A possible solution is to create enough flexibility in the system to ensure more automation during peak workload and greater operator engagement during workload lulls. However, workload itself is a theoretical construct and it is not always obvious how it affects performance. For example, the traditional view of vigilance was that underload was responsible for the observed human performance decrement as a function of time of watch. Recent research indicates that it is overload and not underload that is responsible for the deleterious effects of vigilance [21]. A possible work around would be to leave it up to the operator to decide when to automate and which tasks to automate as mission requirements change. However, this is not always practical because it would burden operators with additional tasks precisely when they are already heavily loaded. For this reason, a number of researcher have suggested using some form of behavioral indicator to change levels of automation dynamically as a function of the changing work environment [22-25].

Adaptive automation uses mitigation criteria that drive an invocation mechanism to maintain an effective mixture of operator engagement and automation for a dynamic multitask environment (Figure 7-7). The invocation mechanism is triggered by whatever measurement process is used to represent the current task state. If properly instrumented the results of the measurement process should be displayed to operators in order to keep them informed of the state of the invocation process.

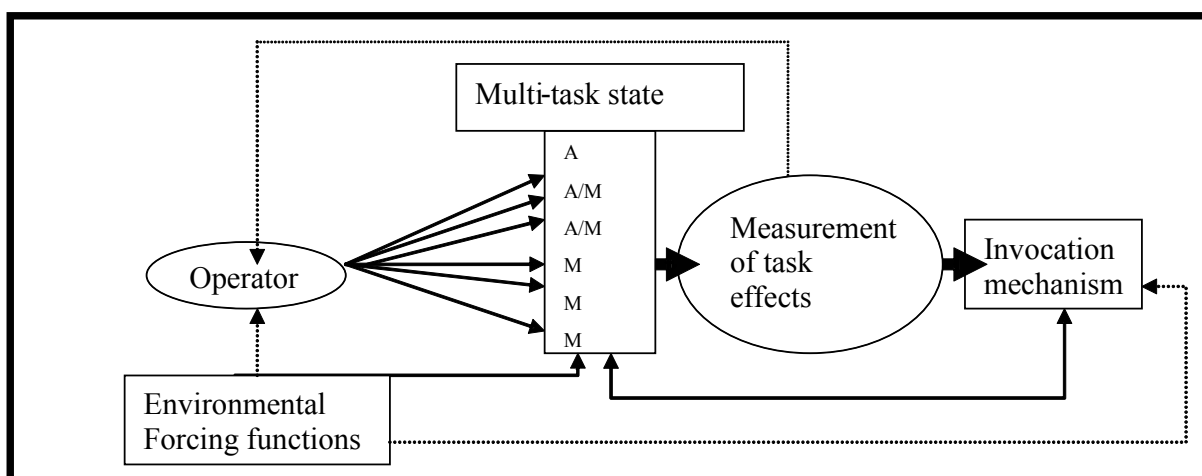


Figure 7-7: Example of a Closed Loop Adaptation for A – Automated, A/M – Automated/Manual, and M – Manual Task Sets.

This construct is more complex than simply unloading (or engaging) the operator because to be effective the invocation process must be sensitive to the operator's combined tasking environment which depends on interactions among tasks as well as overall workload, stress and safety considerations [26]. For example, the algorithm might automate auditory tasks when the communication traffic reaches a predefined level, but not change other task states until the overall workload measure (or physiological index) reaches criterion [27]. Furthermore, whenever certain critical events occur, the invocation mechanism must be sensitive to indices that imply that the operator requires emergency automation (e.g., G-loss of consciousness as evidenced by physiological measurements) [28].

7.4.3 Some Characteristics of Adaptive Automation Systems

7.4.3.1 Invocation Methods

In adaptive systems, the “division of labor” between human and machine agents is not fixed but dynamic, in contrast, to systems where provision of computer aiding is pre-determined at the design stage, and task allocation is fixed during system operations. Although the adaptive automation concept is not new, having been proposed about 25 years ago [29], technologies needed for its effective implementation were not readily available until recently.). A key issue in adaptive automation is the method of invocation. Parasuraman et al. [23] reviewed the major techniques and found that they fell into five main categories:

- Critical events;
- Operator performance measurement;
- Operator physiological assessment;
- Operator modelling; and
- Hybrid methods.

The critical-events method is exemplified by the work of Barnes and Grossman [28]. In this approach, automation is invoked when certain tactical environmental events occur, but not otherwise. For example, in an aircraft air defence system, the beginning of a “pop-up” weapon delivery sequence leads to the automation of all defensive measures of the aircraft. If the critical events do not occur, the automation is not invoked. Hence this method is inherently flexible and adaptive, because it can be tied to current tactics and doctrine during mission planning.

However, a disadvantage of the method is its possible insensitivity to actual system and human operator performance. For example, this method will invoke automation irrespective of whether or not the pilot requires it when the critical event occurs. Operator performance and physiological measurement attempts to overcome this limitation. In these methods, various operator mental states (e.g., mental workload, or more ambitiously, operator intentions) may be inferred on the basis of performance or other measures and then input to adaptive logic. For example, performance and physiological measurements may allow the inference that a human operator is dangerously fatigued or experiencing extremely high workload. An adaptive system could use these measurements to provide computer support or advice to the operator that would mitigate the potential danger. Alternatively, human operator states and performance may be modeled theoretically, with the adaptive algorithm being driven by the model parameters. Intelligent systems that incorporate human intent inferencing models have been proposed [30]. Finally, hybrid methods could be used that combine one or more of these different invocation techniques, so that their relative merits can be maximized.

7.4.3.2 Adaptive and Adaptable Systems

In adaptive systems, the decision to invoke automation or to return an automated task to the human operator is made by the system, using any of the previously described invocation methods. This immediately raises the issue of user acceptance of such a system. Human operators may be unwilling to accede to the “authority” of a computer system that mandates when and what type of automation is or is not to be used. Apart from user acceptance, however, is the issue of system unpredictability and its consequences for operator performance. Billings and Woods [31], for example, raised the caution that truly adaptive systems may be problematic because their behavior may not be predictable to the user. To the extent that automation can hinder the operator’s situation awareness by taking him or her out of the loop, unpredictably invoked automation by an adaptive system may further impair the user’s SA. However, if the automation were explicitly invoked by the user,

then presumably the unpredictability will be lessened – but involving the human operator in making decisions about when and what to automate can increase workload. Thus, there is a tradeoff between increased unpredictability versus increased workload in systems in which automation is invoked by the system or by the user, respectively. Opperman [32] characterized these alternatives as ‘adaptive’ and ‘adaptable’ approaches to system design (see also [33]). In either case, the human + machine system adapt to various contexts, but in adaptive systems automation determines and executes the necessary adaptations, whereas in adaptable systems, the operator is in charge of the desired adaptations. The distinction is primarily one of authority. In an adaptable system, the human always maintains authority to invoke or change the automation, whereas this authority is shared in an adaptive system. Inagaki’s [34] design concept of “situation-adaptive autonomy” is related to this view of an adaptive system, but in his approach, control of a process is traded off between human and computer in real time based on time criticality and the expected costs of human and machine performance.

While in this review we primarily consider how adaptive automation affects system performance, it is important to keep in mind that adaptable automation may provide an alternative approach with its own benefits. The LOA concept introduced by Sheridan [3] does not specify which level should be used or who decides that there should be a change in level.

When the decision is made by a designer prior to system operation, it is a part of system design and corresponds to picking an appropriate LOA for that system design. The decision can also be made by automation itself (or some expert system) during system operators, as a part of a truly adaptive automation system. In both of these cases, the human operator is not involved in the decision. In adaptable systems, however, the human operator is more akin to a supervisor of a human team who delegates tasks to team members, or in this case, to automation. The challenge for developing such an adaptable automation system is that the operator should be able to make decisions regarding the use of automation in a way that does that create such high workload that any potential benefits of delegation are lost.

One such architecture for adaptable automation that can provide for flexible tasking of automation is the “Playbook” [35-37]. The objective of the Playbook interface is to provide a human supervisor the ability to delegate tasks to automation with much of the flexibility available in human-human task delegation, and to do so dynamically at the time of system operation rather than at system design. The Playbook interface facilitates the “teaching” of automation (an idea first proposed by Sheridan [3] when he created the supervisory control concept) by creating a shared knowledge structure of tasks and their relationships within which task performance can be discussed by human and automation. For the Playbook concept to work, the automation must have substantial knowledge about how to perform tasks and achieve goals. This knowledge is also used to improve the efficiency and/or safety of plans developed by allowing automation to review and critique human plans. Finally, Playbooks streamline the process of delegation by the human operator by providing a compiled set of plans, or ‘plays’, with short, easily-commanded labels that can be further modified as needed. This is the critical aspect of the concept that allows this form of adaptable automation not to increase the workload associated with delegation, much as a sports team has an approved set of plays that facilitate task delegation by the team leader. For example, the quarterback in football selects plays that are executed by the team members (the other players).

Support for the efficacy of the Playbook approach to adaptable automation has come from two sources. First, an example Playbook prototype for mission planning tool for commanding Unmanned Combat Air Vehicles (UCAVs) has been developed as a proof-of-concept [37,38]. Second, initial experimental studies of the effects of Playbook interfaces on human performance have been carried out [39,40]. These studies examined the use of a simple Playbook interface on system performance during simulated human-robot teaming using the RoboFlag simulation environment. The RoboFlag Playbook provides the operator the

ability to command simulated robots, individually or in groups, at two levels of granularity: via providing designated endpoints for robot travel or via commanding higher level behaviors (or modes or plays) such as “Patrol Border.” The RoboFlag simulation was modified to emulate a typical unmanned vehicle (UV) mission involving a single operator managing a team of robots. The simulated mission goal was to send the robots from a home area into enemy territory, access and obtain a specified target, and return home as quickly as possible with minimum loss of assets. In the Parasuraman et al. [39] study, the Playbook interface was evaluated as a function of two sources of task demand adversary “posture” in which the enemy engagement style was changed unpredictably between three types, offensive, defensive, or mixed; and environmental uncertainty, as manipulated by variation in the effective visual range of each robotic vehicle under the control of the operator. The results showed that the multi-level tasking of the simplified Playbook interface allowed effective user supervision of robots, as evidenced by the number of missions successfully completed (percent games won) and the time for mission execution. As expected, significantly fewer games were won when the opponent posture was mixed rather than entirely offensive. Nevertheless, users still won a moderately high proportion of games (about 62%) and in a relatively short time (about 51 seconds) in the mixed posture condition. These findings suggest, but do not prove, that the Playbook interface, as a simple example of a delegation interface, allowed users to respond effectively to unexpected changes in opponent posture by tasking robots appropriately. In a subsequent study [40], the Playbook interface was pitted against less flexible interfaces and to manual control, and was found to have significant benefits over both. Further confirmation of the efficacy of the Playbook approach to adaptable automation requires studies in which more complex versions of the Playbook interface are evaluated.

7.4.3.3 Human Interaction with Adaptive Systems

Since the theoretical frameworks for adaptive automation proposed by Rouse [41] and Parasuraman et al. [23], there has been a steady stream of empirical work aimed at examining the effects of adaptive automation on human and system performance in different application domains. The initial studies were designed to investigate whether the performance costs of certain forms of static automation (described previously), such as reduced situation awareness, complacency, skill degradation, etc., can be mitigated by adaptive automation. Most of these studies used either a critical event or model-based approach to adaptive automation. A task was allocated dynamically to either human or machine control at some point in time during a simulated mission, either when some critical event occurred, or as dictated by a simple model of operator and system performance. For example, Hilburn et al. [42] examined the effects of adaptive automation on the performance of military air traffic controllers who were provided with a decision aid for determining optimal descent trajectories of aircraft – a Descent Advisor (DA). The DA was either present at all times (static automation) or came on only when the traffic density exceeded a threshold. Hilburn et al. found significant benefits for controller workload (as assessed using pupillometric and heart rate variability measures) when the DA was provided adaptively during high traffic loads, compared to when it was available throughout (static automation) or only at low traffic loads. In addition to physiological measures of workload, other measures can also be used to assess the workload-leveling effect of adaptive automation. Kaber and Riley [43], for example, used a secondary-task measurement technique to assess operator workload in a target acquisition task. They found that adaptive computer aiding based on the secondary-task measure enhanced performance on the primary task.

The results of these and other studies (see [44] for a review) indicate that adaptive automation can serve to reduce the problem of unbalanced workload, with attendant high peaks and troughs, that static automation often induces. As discussed previously, under high workload operators tend to adopt an attention allocation strategy that results in diminished monitoring of an automated task [11,45]. As a result, operators can miss malfunctions in the task, or fail to correct suboptimal performance by the automation because they are busy

attending to other tasks. Adaptive automation in the form of a temporary return of the automated task to human control can mitigate this so-called complacency effect. In a study with the Multi Attribute Test (MAT) flight simulation battery, Parasuraman et al. [46], showed that temporary return of an automated engine-systems task to human control benefited subsequent operator monitoring of the task when it was returned to automated control. It is important to emphasize that the reallocation to human control was *brief*. If the benefit could only be obtained by prolonged human intervention in the task, that would defeat the purpose of automating the task in the first place. Parasuraman et al. found that the benefit of adaptive reallocation was found for either of two methods of invocation, a model-based approach in which the temporary return to human control was initiated at a particular time specified by the model; and a performance-measurement approach in which the adaptive change was triggered only when the operator's performance on the engine-systems task fell below a specified level. A subsequent study showed that the operator (and system) performance benefit could also be sustained for long periods of time, in principle indefinitely, by repetitive or multiple adaptive task allocation at periodic intervals [47]. Such brief, periodic, adaptive reallocation of an automated task to human control can enhance overall system performance by either maintaining the operator's awareness of the automated task parameters or by refreshing the operator's memory (his or her "mental model") of the automated task behavior. In support of the latter explanation, Farrell and Lewandowsky [48] showed that they could successfully computationally model the complacency effect and the benefit of adaptive reallocation in a three-layer connectionist network with a memory decay function for nodes representing automation performance.

These results show that adaptive automation can balance operator workload and reduce automation complacency. However, Parasuraman et al. [46] also showed that performance benefits can be eliminated if adaptive automation is implemented in a clumsy manner, supporting the concerns of Billings and Woods [31]. Moreover, these studies, while clearly pointing to the potential benefit of adaptive automation, had some limitations. The model-based invocation method used in many of the studies has the advantage that the model can be implemented off-line and easily incorporated into rule-based expert systems. However, this method requires a valid model, and many models may be required to deal with all aspects of human operator performance in complex task environments.

7.4.4 Physiological Measurement Techniques

There are many ways in which the system changes can be initiated: subjective workload assessments, operator performance and physiological measures. The final section will discuss physiological measurement processes and their relationship to adaptation. Operator physiological assessment offers another potential input for adaptive systems [49,23]. Physiological measures can provide additional information that can be tapped for control of adaptive systems. Technology is available to measure a number of physiological signals from the operator, from autonomic measures such as heart rate variability to central nervous system measures such as the EEG and event-related potentials or ERPs, as well as measures such as eye scanning and fixations. Measurement technology is developing rapidly showing improvements in the areas of non-intrusiveness, precision and prediction. For these reasons, the authors felt it was important to survey these methods in some detail. The goal of using physiological methods for adaptive automation is to enhance operator performance by restructuring the environment and or adjusting the demands of the situations [50]. The emphasis is on the operator's capabilities not the system's [49].

One way in which systems may be able to enhance operator performance is via online measures of workload. According to Scerbo, Freeman, and colleagues [51] mental workload is the critical factor in determining when and what type of system changes need to be made. There are individual differences in how a person handles the demands of a situation and these individual differences may impact on performance. According to Gopher

and Donchin [52] people often increase their mental and physical effort as task load increases. The concept of workload is used to account for the aspect of the interaction between the person and the task that cause task demands to exceed the person's capacity to successfully complete the task. The concept of workload implies that there are limitations in information processing capacity. Two theories form the foundation of much of the research conducted on adaptive automation, Kahneman's Capacity and Resource Theory and Wicken's Multiple Resource Theory [22]. According to Kahneman, information processing resources are limited, but are a function of arousal. As task load increases, arousal increases beyond an optimal level causing cognitive capacity to decrease. In single resource theory, capacity can be allocated to different tasks but the result is a depletion of overall capacity. According to Wicken's multiple resource theory, information processing resources are limited but this limitation is a function of the type of mental resource being used (i.e., visual, auditory). Capacity decreases more when two task are sharing the same resources than when they are using different resources. The models are not mutually exclusive; Wickens, Dixon and Chang [27] recently found that a combination of single resource and multiple resource models best described operator performance for controlling two unmanned vehicles in a multi-task environment.

There is now a substantial literature indicating that different psychophysiological measures can be used for real-time assessment of mental workload [53-56]. Researchers have examined the use of Heart Rate (HR), Heart Rate Variability (HRV), Electroencephalography (EEG), Event Related Potentials (ERP), Transcranial Doppler Sonography (TCD), Functional Magnetic Resonance Imaging (fMRI) and more recently Functional Near Infrared Imaging (fNIR). Prinzel, Freeman, Scerbo, Mikulka, and Pope [57] have also specifically demonstrated the feasibility of an adaptive system based on EEG measures. Each of these measures has advantages and disadvantages and we discuss their potential utility in an adaptive automation system. An overview of the most likely indices, limitations and advantages is presented in Table 7-4. A more detailed review can be found in Scerbo, Freeman, Mikulka, Parasuraman, DiNocera and Prinzel [51].

Table 7-4: Matrix of Physiological Measures – Advantages and Disadvantages

Measures		What does it measure?	Advantages	Disadvantages	How Can The Measure Be Used?
Electroencephalography	EEG	-Electrical activity of neuronal assemblies - Recorded potential reflects cortical activity in area under electrode	-Good temporal resolution -Localization of a behavior to a cortical region -Extensive research base -New systems more field practical	-Affected by artifacts such as muscle activity and heart beats -Poor spatial resolution	-Assess cortical involvement in different contexts and situations (e.g. effect of practice on cerebral activity)
Event Related Potentials (Derived from EEG)	ERP	-Component of EEG related specifically to a stimulus -Discrete time locked responses to a stimulus	-Good temporal resolution -Can examine time-based changes in cortical activity to a stimulus	-Affected by artifacts such as eye blinks and heart activity -Poor spatial resolution	-Assess time locked changes in cortical involvement in different contexts and situations
Transcranial Doppler Sonography	TCD	-Blood flow velocity in the main stem intra-cranial arteries	-Good spatial & temporal resolution -Non-invasive -Less restrictive than other brain imaging techniques (e.g. EEG) -Low-cost & field practical	-Can not identify the specific brain area utilizing the metabolic resources (i.e. blood flow) -Relatively new measurement technique	-Potential metric for cognitive readiness -Assess how information-processing resources are utilized and distributed in different situations
Functional Magnetic Resonance Imaging	fMRI	-BOLD response (blood oxygenation level response), i.e., cerebral blood flow	-Excellent spatial resolution -Extensive medical research base, growing cognitive science base	-Less good temporal resolution -Expensive -Restrictive environment	-As with EEG, ERP, and others, good for cognitive modeling validation
Functional Near Infrared Imaging Devices	fNIR	-Light is transmitted and the reflected light from the cortical level is encoded and reconstructed into a map of brain activity	-Non-invasive -Less restrictive than other brain imaging techniques (e.g. EEG) -Field practical	-New technology -Still in development -Unable to measure signals from deep brain tissue	-Real time assessment of warfighter's cognitive state that can be utilized in operational environments
Heart Rate Variability (Derived from an electrocardiogram)	HRV	-Cardiac activity	-Assess the variability in R-R intervals -Discriminate between parasympathetic and sympathetic influences on the heart	-Influenced by respiratory changes	-HRV related to changes in cortical brain areas -Changes in HRV may be related to cognitive events and individual differences

7.4.4.1 Heart Rate and Heart Rate Variability

Cardiac activity is measured by electrocardiogram (ECG/EKG). An ECG records the electric activity generated by the action potentials of the cardiac muscle cells. Two measures of cardiac activity that can be derived from an ECG are heart rate and heart rate variability. Heart rate is measured in beats per minute. Research has shown that heart rate increases with increases in workload demands [51]. There is variability in the heart cycle. This variability is called Heart Rate Variability (HRV) which can be measured in the time or frequency domain. Research has suggested that variation in HRV may be used to differentiate between levels of task difficulty, the type of task and mental workload. For example, the more effort a task requires, the greater the suppression of HRV. Nickel and Nachreiner [58] examined if the .1 Hz component of HRV can discriminate between levels of workload. Results showed that the .1 Hz component discriminated between periods of work and rest. However, HRV was not different between types of tasks or level of task difficulty suggesting that task demands must be very high for the HRV components to be able to discriminate between workload conditions. In general, cardiac activity is probably the most commonly used measure in workload assessment [59]. HR and HRV may reflect energetic arousal, emotional processes and cognitive processes that may impact on task performance [58]. Cardiac activity can be easily measured and with the development of small telemetric systems it is a field practical measure.

7.4.4.2 Electrocortical Activity

7.4.4.2.1 Electroencephalography (EEG)

EEG is a non-invasive recording of the fluctuations in electrical activity of large ensembles of neurons in the brain which is taken from the scalp. Activity can be measured from numerous locations and across various bandwidths (e.g., alpha 8-12 Hz). There is an extensive research base on EEG activity during various cognitive tasks. For example, Gevins, Smith, Leong, McEvoy, Du and Rush [53] showed that neural networks could be used to discriminate differences in memory load based on EEG. In the adaptive automation literature, a general assumption is made that changes in EEG reflect arousal and workload [51]. Pertinent to our research interests, Scerbo and colleagues (e.g., [57]) have conducted an elegant series of experiments which use EEG to drive adaptive automation. It is a closed-loop system that moderates workload by decreasing the task demands when workload increases. Increases in workload are assessed via EEG. EEG is measured and an EEG engagement index is derived from components of the frequency domain. The system allocates the tasks based on the engagement index. A high engagement index is related to a high state of alertness and an increased ability to attend to stimuli [60]. The MAT task is used as the test-bed. There is a monitoring task, resource management task, communications task and a tracking task. The tracking task shifts between manual and automated depending on the engagement ratio of the operator. Tracking performance improved using an adaptive policy wherein high engagement EEG ratios invoked automation and low ratios invoked manual tracking compared to the opposite invocation policy (non-adaptive – switch to auto-low and manual-high). Prinzel et al. [57] showed that when the engagement index increased and the system automated the task, performance on the tracking task was better than when the task was always in the manual condition. Further, Prinzel, Pope and Freeman [61] provided biofeedback about the participants' performance and engagement level, which improved performance on the tracking task during automation and when the task was returned to manual. The engagement index modifies the system to meet the real-time needs of the operator and as a result improves performance. Using biofeedback, the participant was aware of his/her state which allowed the participant to be an active participant in the task environment.

However, these studies failed to show that other invocation policies or simply automating the tracking task would not have been as effective. For example, a recent study by Mikulka, Scerbo and Freeman [50] used a similar paradigm to investigate vigilance performance under low, medium and high event rates. They also

introduced a control to ensure that the invocation policies based on the EEG's were the cause of the performance differences. Each EEG participant had a yoked partner who switched to automation (or manual) mode in the same time hack and task level (unrelated to his or her EEG state) as the EEG partner. The group that had an adaptive EEG policy was again superior to the non-adaptive EEG engagement policy group. However, the yoked groups followed the same pattern implying that the results were caused by task difficulty and switching policy and not the EEG indices per se. This suggest that modeling the task environment might be as effective as using the EEG engagement policy. In summary, EEG based invocation policies show promise, but more research needs to be conducted to confirm their superiority in complex task environments in comparison to automated systems and to other invocation policies.

7.4.4.2.2 Event Related Potentials (ERP)

An EEG based system such as the one described above is triggered by gross changes in the level of engagement and may not be sensitive to different types of task and levels of task difficulty [63]. An ERP is a component of EEG related specifically to the presentation of a stimulus. It is an average of the EEG at the electrode sites of interest; a time locked response to a stimulus. ERPs are characterized by their polarity (positive or negative) and time of occurrence (latency from the onset of the stimulus). An ERP may reflect various information processing activities such as attention, intention and expectation. For example, the P300 reflects the availability and distribution of information processing resources and it may be sensitive to changes in workload. Prinzl et al. [62] assessed the sensitivity of the P300 to changes in workload and performance. Participants completed the MAT task (with or without adaptive automation) and an auditory oddball task in which they counted the number of high tones. Performance was better on the tracking and auditory task in the adaptive automation condition relative to the control and yoked control. Further, the amplitude of the P300 was greater in the adaptive automation condition than the control and yoked control condition. The amplitude of the P300 may be proportional to the attentional resources "invested" in the task. Kramer, Trejo and Humphrey [54] suggest that ERPs may be used to detect variations in workload. Kramer et al. had participants complete a radar monitoring task during which time task-irrelevant auditory probes were presented. The ERP amplitude (i.e., N100, N200), elicited by the deviant auditory probe, decreased as task load increased. Results showed that ERPs are sensitive to task type and level of task difficulty. Further, Prinzl and colleagues [62] suggest that the P300 may be an indicator of the efficacy of the adaptive automation and may also be used as a trigger for it.

In summary, electrocortical activity has been used with limited success in adaptive automation. It is important to note that as with all measurement techniques, EEG and ERPs are not without limitations. These measurements are not sensitive enough to assess activity in narrow cortical regions. EEG and ERPs have poor spatial resolution. Further, the EEG signal can be affected by artifacts such as muscle activity and heartbeats. Filtering techniques can be used to eliminate some of the artifacts from the EEG. Researchers must be cautious when filtering their data that they do not filter out the EEG signal as well as the artifact. Current EEG systems are not field practical, but advances in technology are being made and systems are being designed to be more robust and field-ready.

7.4.4.3 Blood Flow

7.4.4.3.1 Positron Emission Tomography (PET) and Functional Magnetic Resonance Imaging (fMRI)

Brain imaging studies using PET and fMRI measures of cerebral blood flow have revolutionized cognitive psychology. There is hardly a domain of cognition where such measures have not been used to localize elements of cognitive function within the brain. It is therefore not surprising that researchers have also

attempted to examine whether these measures might be used for investigating more applied aspects of cognition such as mental workload.

The notion of mental workload as reflecting how hard one's mind is working at any given moment is intuitively appealing. Given that the mind is a function of the brain, it follows that mental work should be associated with *brain* work [63]. Brain work can be linked to both global and local changes in cerebral blood flow associated with mental activity. Sir Charles Sherrington, the great 19th century physiologist, first suggested that brain work was related to the regulation of the blood supply of the brain. Sherrington demonstrated that there is a close coupling between the electrical activity of neuronal cells, the energy demands of the associated cellular processes, and regional blood flow in the brain. His pioneering work suggested (but did not prove, since he lacked the technology) that if mental activity results in increased neuronal response in localized regions of the brain, then mental work could be assessed by measuring regional cerebral metabolism and blood flow. Autoradiographic studies in animals later confirmed Sherrington's principle for the regulation of brain blood flow and its coupling to neuronal activity and energy usage – but it would take several years before sensitive techniques were developed for measuring regional brain blood flow in humans. The development of PET paved the way for less invasive measurement of regional cerebral metabolism and blood flow in humans. PET is an adaptation of autoradiographic techniques originally developed for measuring blood flow in animals. Regional cerebral glucose metabolism can be non-invasively determined using PET and radioactively labeled glucose (18-fluoro-deoxyglucose), while regional cerebral blood flow may be assessed with PET and radioactively-labeled oxygen (O-15) in water.

PET is more accurate than the older methods in localizing the specific cortical regions activated by cognitive task demands. Nevertheless, the spatial resolution of PET, particularly in individual subjects, could be improved. Furthermore, the need for ionizing radiation, although safe when used within exposure limits, is an impediment against frequent use in studies with normal human subjects. The recent development of fMRI has overcome both these limitations. fMRI provides non-invasive, high-resolution assessment of regional cerebral blood flow.

How do PET and fMRI compare with EEG or ERP measures of cognition and mental workload? Because brain electrical activity is recorded from the scalp, the EEG or the ERP, while having excellent temporal resolution in identifying the neural correlates of mental processing, do not provide strong evidence for the localization of neural activity associated with mental workload. The poor spatial resolution of EEG and ERPs can be overcome to a degree through the use of such techniques as dipole modeling and spatial deconvolution. For example Gevins et al. [64] reported that midline frontal EEG theta activity is a correlate of mental workload. This EEG signal is thought to be generated in the anteromedial frontal cortex, possibly the anterior cingulate cortex which has also been proposed to be a high-level central executive control center on the basis of PET and lesion studies. In general, however, brain imaging techniques offer superior spatial resolution to EEG/ERPs and have provided recent evidence on the cortical localization of mental workload.

7.4.4.3.2 *Blood Flow Velocity*

Cerebral blood flow velocity (BFV) is assessed by Transcranial Doppler Sonography (TCD). TCD is used to assess the hemodynamic changes in the major cerebral arteries [65]. More specifically, TCD measures moment-to-moment changes in blood flow velocity (BFV). BFV values are obtained by recording frequency shifts in the ultrasound that is reflected from the blood flowing the cerebral artery. The frequency shifts are recorded by spectral analysis.

TCD could possibly be used to 'quantify attentional effort' [66]. Changes in BFV may reflect the changes in attention. According to the resource utilization model, demanding tasks consume more processing resources

than less demanding tasks [67]. When there is a decrease in performance this may reflect a depletion of the information processing resources. The amount of resources available may be related to BFV. For example, Maybelen [68] showed that as performance on vigilance tasks declined, there was a decrease in blood flow velocity over time. The amount of blood flow was also dependent on the type of task utilized; an absolute judgment task was associated with greater amount of blood flow and a greater decrease in blood flow over time than a comparative judgment task.

Hitchcock et al. [66] compared the blood flow during a vigilance task. Participants were presented low or high salience cues that were presented at various intervals during the experiment (e.g., high salience cues were presented 40% of the time). Results showed that for low salience cues there was a greater amount of blood flow and a greater decrease in blood flow over time in the right cerebral artery relative to that for high salience cues which were detected more often. The authors suggested that blood flow may be an index of the expenditure of information processing resources, which is greater for low than high salience cues.

TCD is a low cost non-invasive diagnostic tool. Unlike other measures of brain activity, such as fMRI or EEG, TCD has good temporal resolution while placing participants under less restrictive conditions. TCD may be able to be used in a laboratory or field setting. The use of TCD would allow researchers the flexibility to examine military issues in an appropriate context without the restrictions imposed by other measurement techniques. The disadvantage of TCD is that it has poor spatial resolution; researchers are only able to generalize the BFV to a cerebral artery. The cortical region that is utilizing the metabolic resources can not be identified. Furthermore, this is a relatively new technique in cognitive psychology and has not been used in adaptive automation applications.

7.4.4.4 Hybrid Measures

It is possible that one physiological measure will not be able to capture the complexity inherent in human performance. Wilson, Lambert and Russell [69] used a multiple measure approach to design a physiologically based adaptive automotive system. Wilson et al. had participants complete the MAT task with two levels of difficulty (varied the number of events that occurred in five minutes). EEG, ECG, EOG and respiration were measured during the task. Wilson et al. trained an artificial neural network (ANN) to recognize the physiological patterns that differentiate states of rest, low task difficulty and high task difficulty. The ANN was then used to determine which condition a participant was performing and when the high difficulty task was detected the monitoring and auditory task were automated. Results showed that the ANN correctly identified the task conditions and when adaptive automation was implemented tracking error decreased and performance on the resource management task increased compared to the manual condition. No comparison was made between fully and adaptively automated performances. (Wilson et al.).

7.4.4.5 Measurement Conclusions

Most of the measures were based on the premise that the measures are physiological correlates of workload and that as the human operator's workload increases beyond a certain point performance will start to deteriorate. Correlations with perceived workload and increased task difficulty have been shown for a number of the above indices. Some are currently not usable in a combat environment and others are not precise enough to be useful in their current configuration. However, these limitations are being overcome rapidly and the developing technology will soon be practical and precise enough for future combat systems. One of the most promising technologies is one of the oldest: EEG. However, the initial results are pertinent to artificial task environments and the usefulness of an adaptive systems based on EEGs has not been established. More research needs to be done in the following areas:

- 1) Establish the usefulness of these measures for adaptive and adaptable processes compared to non-adaptive automation and manual control in complex environments.
- 2) Compare various adaptive invocation policies in these environments.
- 3) Investigate some of the newer techniques (including the neural net modeling) as their precision and practicality increases.

7.4.5 General Conclusions

Future combat environments will be radically different with robotic and automated systems becoming a ubiquitous component of future aerial and ground inventories. The authors discussed human performance advantages and disadvantages of battlefield automation and concluded:

- 1) A review of the human performance literature suggests that soldiers tend to both over rely and under rely on automated systems depending on the following factors:
 - Decision order;
 - Operator overload;
 - False alarm rate; and
 - Reliability of the system.
- 2) Poorly designed automation resulted in loss of situation awareness and operator complacency.
- 3) Adaptive and adaptable automated systems were evaluated as flexible alternatives to preset automation.
- 4) Various physiological measures were contrasted as potential components of adaptive systems in terms of their relative maturity and intrusiveness.
- 5) Although some of these measures were extremely promising as non-intrusive indexes of operator loading; more research is needed before practical adaptive or adaptable systems can be fielded.

7.4.6 References

- [1] Woods, D. (1996). Decomposing automation: Apparent simplicity, real complexity. In: R. Parasuraman and M. Mouloua (Eds). Automation and human performance: theory and application. Human factors in transportation (pp. 3-17) Mahwah NJ: Lawrence Erlbaum Associates.
- [2] Barnes, M.J., Wickens, C.D. and Smith, M. (2000). Visualizing uncertainty in an automated National Missile Defense simulation environment. Proceedings of the 4th Annual FedLab Symposium: Advanced Displays and Interactive Displays (pp. 117-122). Adelphi, MD: U.S. Army Research Laboratory.
- [3] Sheridan, T.B. (1992). Telerobotics, automation, and supervisory control. Cambridge, MA: MIT Press.
- [4] Parasuraman, R., Sheridan, T.B. and Wickens, C.D. (2000). A model for types and levels of human interaction with automation. IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans, 30, 286-297.

- [5] Parasuraman, R. and Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors*, 39, 230-253.
- [6] Mosier, K.L. and Skitka, L.J. (1996). Human decision makers and automated decision aids: Made from each other? In: R. Parasuraman and M. Mouloua (Eds). *Automation and human performance: theory and application. Human factors in transportation* (pp. 163-176) Mahwah NJ: Lawrence Erlbaum Associates.
- [7] Dzindolet, M.T., Pierce, L.G., Beck, H.P., Dawe, L.A. and Anderson, B.W. (2001). Predicting misuse and disuse of combat identification systems. *Military Psychology*, 13(3), 147-164.
- [8] Dzindolet, M.T., Pierce, L.G., Beck, H.P. and Dawe, L.A. (2002). The perceived utility of human and automated aids in a visual detection task. *Human Factors*, 44(1), 79-94.
- [9] Dzindolet, M.T., Beck, H.P., Pierce, L.G. and Dawe, L.A. (2001). A framework for automation use (ARL-TR-2412) Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.
- [10] Parasuraman, R. and Byrne, E.A. (2003). Automation and human performance in aviation. In: P. Tsang and M. Vidulich (Eds.) *Principles of Aviation Psychology*. (pp. 311-356). Mahwah, NJ: Erlbaum.
- [11] Parasuraman, R., Molloy, R. and Singh, I.L. (1993). Performance consequences of automation-induced "complacency." *The International Journal of Aviation Psychology*, 3, 1-23.
- [12] Singh, I.L., Molloy, R. and Parasuraman, R. (1997). Automation-related monitoring inefficiency: The role of display location. *International Journal of Human-Computer Studies*, 46, 17-30.
- [13] Barnes, M. (2003). Human dimension of battlefield visualization: Research and design issues (ARL-TR- 2885). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.
- [14] Wickens, C. and Hollands, J. (2000). *Engineering psychology and human performance*. Upper Saddle River, NJ: Prentice Hall.
- [15] Meyer, J. (2001). Effects of warning validity and proximity on responses to warnings. *Human Factors*, 43, 563-572.
- [16] Dixon, S. and Wickens, C.D. (2003). Imperfect automation in unmanned aerial vehicle flight control. (AHFD)-03-1/MAAD-03-1) Savoy, IL: University of Illinois Research Lab.
- [17] Rovira, E., McGarry, K. and Parasuraman, R. (2004). Effects of imperfect automation on decision making in a simulated command and control task. Under review, *Human Factors*.
- [18] Galster, S.M. and Parasuraman, R. (2003). The application of a qualitative model of human-interaction with automation in a complex flight task. In: *Proceedings of the 12th International Symposium of Aviation Psychology*, 411-416, Dayton, Ohio: Ohio State University.
- [19] Lorenz, B., DiNocera, F., Rottger, S. and Parasuraman, R. (2002). Automated fault management in a simulated space flight micro-world. *Aviation, Space and Environmental Medicine*, 73, 886-897.
- [20] Endsley, M. (1996). Automation and situation awareness. *Automation and human performance: theory and application. Human factors in transportation* (pp. 163-179) Mahwah NJ: Lawrence Erlbaum Associates.

- [21] Warm, J., Dember, W.N. and Hancock, P. (1996). Vigilance and workload in automated systems. In: R. Parasuraman and M. Mouloua (Eds.) *Automation and human performance: Theory and applications*. (pp. 183-200). Mahwah, NJ: Erlbaum.
- [22] Byrne, E.A. and Parasuraman, R. (1996). Psychophysiology and adaptive automation. *Biological Psychology*, 42, 249-268.
- [23] Parasuraman, R., Bahri, T., Deaton, J.E., Morrison, J.G. and Barnes, M. (1992). Theory and design of adaptive automation in aviation systems. (Technical Report No. NAWCADWAR-92033-60). Warminster, PA: Naval Air Warfare Center, Aircraft Division.
- [24] Rouse, W.B. (1977). Human-computer interaction in multi-task situations. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-7, 384-392.
- [25] Scerbo, M.W. (1996). Theoretical perspectives on adaptive automation. In: R. Parasuraman and M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 37-63). Mahwah, NJ: Lawrence Erlbaum Associates.
- [26] Wickens, C. and Hollands, J. (2000). *Engineering psychology and human performance*. Upper Saddle River, NJ: Prentice Hall.
- [27] Dixon, S., Wickens, C.D. and Chang, D. (2004). Unmanned aerial vehicle flight control: False alarms versus misses. In: *Proceedings of the 48th Annual Human Factors and Ergonomics Society Meeting*. New Orleans, LA.
- [28] Barnes, M. and Grossman, J. (1985). The intelligent assistant for electronic warfare systems (NWC TP 5885) China Lake CA: US Naval Weapons Center.
- [29] Rouse, W.B. (1976). Adaptive allocation of decision making responsibility between supervisor and computer. In: T.B. Sheridan and G. Johanssen (Eds.), *Monitoring behavior and supervisory control* (pp. 295-306). New York: Plenum Press.
- [30] Geddes, N. (1985). Intent inferencing using scripts and plans. In: *Proceedings of the First Annual Aerospace Applications of Artificial Intelligence Conference*. (pp. 123-127). Washington DC: AAAI.
- [31] Billings, C.E. and Woods, D. (1994). Concerns about adaptive automation in aviation systems: In: R. Parasuraman and M. Mouloua (Eds.), *Automation and human performance: Current research trends* (pp. 264-269) Hillsdale NJ: Lawrence Erlbaum Associates.
- [32] Opperman, R. (1994). *Adaptive User Support*. Hillsdale, NJ; Erlbaum.
- [33] Scerbo, M. (2001). Adaptive automation. In: W. Karwowski (Ed.) *International encyclopedia of human factors and ergonomics*. London: Taylor and Francis, Inc.
- [34] Inagaki, T. (1999). Situation-adaptive autonomy: Dynamic trading of authority between human and automation.
- [35] Miller, C., Pelican, M. and Goldman, R. (2000). 'Tasking' interfaces for flexible interaction with automation: Keeping the operator in control. In: *Proceedings of the Conference on Human Interaction with Complex Systems*. Urbana-Champaign, IL.

- [36] Miller, C. and Parasuraman, R. (2003). Beyond levels of automation: An architecture for more flexible human automation collaboration. In: Proceedings of The Human Factors and Ergonomics Society, Denver, CO, October 2003.
- [37] Miller, C. and Parasuraman, R. (2002). Designing for flexible human-automation interaction: Playbooks for supervisory control, Technical Report, SIFT, MN.
- [38] Miller, C., Pelican, M. and Goldman, R. (2000). 'Tasking' interfaces for flexible interaction with automation: Keeping the operator in control. In: Proceedings of the Conference on Human Interaction with Complex Systems. Urbana-Champaign, IL.
- [39] Parasuraman, R., Galster, S. and Miller, C. (2003). Human control of multiple robots in the RoboFlag simulation Environment. In: Proceedings of the 2003 IEEE International Conference on Man, Systems and Cybernetics. Washington, DC.
- [40] Squire, P.N., Galster, M. and Parasuraman, R. (2004). The effects of levels of automation in the human control of multiple robots in the RoboFlag simulation environment. In: D.A. Vincenzi, M. Mouloua and P.A. Hancock, Human Performance, Situation Awareness, and Automation Volume II (pp. 48-53). Mahwah, NJ: Erlbaum.
- [41] Rouse, W.B. (1988). Adaptive aiding for human-computer control. Human Factors. 30, 431-441.
- [42] Hilburn, B., Jorna, P.G., Byrne, E.A. and Parasuraman, R. (1997). The effect of adaptive air traffic control (ATC) decision aiding on controller mental workload. In: M. Mouloua and J. Koonce (Eds.), Human-automation interaction: Research and practice (pp. 84-91). Mahwah, NJ: Erlbaum Associates.
- [43] Kaber, D.B. and Riley, J.M. (1999). Adaptive automation of a dynamic control task based on secondary task workload measurement. International Journal of Cognitive Ergonomics, 3, 169-187.
- [44] Parasuraman, R. (2000). Designing automation for human use: Empirical studies and quantitative models. Ergonomics, 43, 931-951.
- [45] Moray, N., Inagaki, T. and Itoh, M. (2000). Adaptive automation, trust, and self-confidence in fault management of time-critical tasks. Journal of Experimental Psychology – Applied, 6, 44-58.
- [46] Parasuraman, R., Mouloua, M. and Hilburn, B. (1999). Adaptive aiding and adaptive task allocation enhance human-machine interaction. In: M.W. Scerbo and M. Mouloua (Eds.) Automation technology and human performance: Current research and trends. (pp. 119-123). Mahwah, NJ: Erlbaum.
- [47] Mouloua, M., Molloy, R. and Parasuraman, R. (1993). Monitoring automation failures: Effects of single and multiadaptive function allocation. In: Proceedings of the Annual Meeting of the Human Factors Society, Human Factors Society, Santa Monica, CA, pp. 1-5.
- [48] Farrell, S. and Lewandowsky, S. (2000). A connectionist model of complacency and adaptive recovery under automation. Journal of Experimental Psychology: Learning, Memory, and Cognition 26, 395-410.
- [49] Byrne, E.A. and Parasuraman, R. (1996). Psychophysiology and adaptive automation. Biological Psychology, 42, 249-268.

- [50] Mikulka, P.J., Scerbo, M.W. and Freeman, F.G. (2002). Effects of a biocybernetic system on vigilance performance. *Human Factors*, 44(4), 654-664.
- [51] Scerbo, M.W., Freeman, F.G., Mikulka, P.J., Parasuraman, R., DiNocera, F. and Prinzel, L.J. (2001). The efficacy of psychophysiological measures for implementing adaptive technology. (Technical Report No. NASA/TP-2001-211018). Hampton VA: NASA, Langley Research Center.
- [52] Gopher, D. and Donchin, E. (1986). Workload: An examination of the concept. In: K. Boff, L. Kauffman, and J.P. Thomas (Eds.), *Handbook of Perception and Human Performance*, (pp. 41.1-41.49). New York: Wiley & Sons.
- [53] Gevins, A.S., Smith, M.E., Leong, H., McEvoy, L., Du, R. and Rush, G. (1998). Monitoring memory load during computer-based tasks with EEG pattern recognition methods. *Human Factors*, 40, 79-91.
- [54] Kramer, A.F., Trejo, L.J. and Humphrey, D.G. (1996). Psychophysiological measures of workload: Potential applications to adaptively automated systems. In: R. Parasuraman and M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 137-162). Mahwah, NJ: Lawrence Erlbaum Associates.
- [55] Parasuraman, R. (1990). Event-related brain potentials and human factors research. In: J.W. Rorbaugh, R. Parasuraman and R. Johnson (Eds.), *Event-related potentials: Basic and applied issues* (pp. 279-300). New York: Oxford University Press.
- [56] Scerbo, M.S., Freeman, F.G., Mikulka, P.J., Parasuraman, R., Di Nocera, F. and Prinzel, L.J. (2001). The efficacy of psychophysiological measures for implementing adaptive technology. Technical Paper NASA/TP-2001-211018. Hampton, VA: NASA Langley Research Center.
- [57] Prinzel, L.J., Freeman, F.G., Scerbo, M.W., Mikulka, P.J. and Pope, A.T. (2000). A closed-loop system for examining psychophysiological measures for adaptive automation. *International Journal of Aviation Psychology*, 10, 393-410.
- [58] Nickel, P. and Nachreiner, F. (2003). Sensitivity and diagnosticity of the 0.1-Hz component of heart rate variability as an indicator of mental workload. *Human Factors*, 45(4), 575-590.
- [59] Lenneman, J.K. and Backs, R.W. (2000). The validity of factor analytically derived cardiac autonomic components for mental workload assessment. In: Backs, R.W. and Boucsein, W. (Eds.), *Engineering Psychophysiology: Issues and Applications*. Mahwah, NJ: Lawrence Erlbaum.
- [60] Freeman, F.G., Mikulka, P.J., Prinzel, L.J. and Scerbo, M.W. (1999). Evaluation of an adaptive automation system using three EEG indices with a visual tracking task. *Biological Psychology*, 50(1), pp. 61-76.
- [61] Prinzel, L.J., Pope, A.T. and Freeman, F.G. (2001). Physiological self-regulation and adaptive automation. *The International Journal of Aviation Psychology*, 12, 179-196.
- [62] Prinzel, L.J., Freeman, F.G., Scerbo, M.W., Mikulka, P.J. and Pope, A.T. (2000). A closed-loop system for examining psychophysiological measures for adaptive automation. *International Journal of Aviation Psychology*, 10, 393-410.

- [63] Parasuraman, R. and Caggiano, D. (2002). Mental workload. In: V.S. Ramachandran (Ed.) Encyclopedia of the human brain. San Diego: Academic Press.
- [64] Gevins, A. and Smith, M.E. (2003). Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomic Science*, 4, 113-131.
- [65] Stroobant, N. and Vingerhoets, G. (2000). Transcranial doppler ultrasonography monitoring of cerebral hemodynamics during performance of cognitive tasks: A review. *Neuropsychology Review*, 10, 213-231.
- [66] Hitchcock, E.M., Warm, J.S., Dember, W.N., Matthews, G.R., Shear, P.K., Rosa, R.R., Tripp, L., Mayleben, D.W. and Parasuraman, R. (2000). Proceedings of the Human Factors and Ergonomic Society 44th Annual Meeting (3-382 – 3-385).
- [67] Parasuraman, R., Warm, J.S. and Dember, W.N. (1987). Vigilance: Taxonomy and utility. In: L.S. Mark, J.S. Warm and R.L. Huston (Eds.) *Ergonomics and human factors: Recent research*. (pp. 11-32). New York: Springer-Verlag.
- [68] Maybelen, D. (1998). Cerebral blood flow during sustained attention. Unpublished doctoral dissertation. University of Cincinnati, Cincinnati, OH.
- [69] Wilson, G.F., Lambert, J.D. and Russell, C.A. (2000). Performance enhancement with real-time psychophysiological controlled adaptive aiding. Proceedings of the Army Science Conference, ASC00-0350.

7.5 DESIGNING FOR FLEXIBLE HUMAN-AUTOMATION INTERACTION: PLAYBOOKS FOR SUPERVISORY CONTROL

As systems become more complex, there is increasing temptation to control them via “automation” – that is, a device, machine, or system that accomplishes, fully or partially, a function which was or could be performed by a human [1]. Examples of this trend are rife in domains ranging from aviation and air traffic management to health care and bioinformatics [2-4].

Automation can provide clear benefits. Billings [2] documents payoffs of increased automation in commercial aviation in four key areas: safety, reliability, economy, and comfort – but automation has also been shown to pose novel problems for human operators in some circumstances: to increase workload and training requirements, to result in decreased situation awareness and, in specific instances, to cause accidents (e.g., [1,5-7]).

This ‘double-edged sword’ of automation use [8] has motivated repeated questions about which tasks should be automated to which level or degree for optimal control, performance, and safety. Technologists tend to push to automate tasks as fully as possible – what has been called the ‘technological imperative’ [9]. Human factors engineers and others concerned with safety and the human role in advanced systems have tended to highlight the risks of increased automation (e.g., [10-12]) and to argue against the use of higher levels of automation, especially if the human role in the resulting system is decided by default.

An approach to human-automation relationships that retains the benefits of automation while minimizing its costs and hazards is needed. For reasons discussed below, we believe that such an approach requires that neither human nor automation be exclusively in charge of most tasks, but rather demands flexibility in the role and level of automation while placing control of that flexibility in the human operator’s hands. This implies

that, for most tasks, automation levels should be at neither end of a possible spectrum, but rather at some intermediate, and *adjustable*, point. Human operators need to be able to delegate tasks to automation, and receive feedback on their performance, in much the same way that delegation can be performed in successful human-human teams and organizations: at various levels of detail and granularity, and with various constraints, stipulations, contingencies, and alternatives.

In this paper, we begin by reviewing the literature supporting the advantages of a delegation-based, intermediate approach to human-automation relationships. Then we examine traditional approaches to characterizing automation levels and discuss why a delegation approach demands they be extended to explicitly represent task decomposition. Finally, we present one specific implementation of a delegation approach, based on a sports team ‘playbook’ metaphor.

7.5.1 Intermediate Automation Levels-Costs of Automation Extremes

The promised, and frequently realized, benefits of automation have generally been sufficient to argue against relegating many tasks to the lowest levels of automation—purely manual performance. The economic benefits of automation are a strong, but not the only, motivator. Automation does offer substantial benefits in human workload reduction, increased performance and safety, when it is properly designed and used [1,2,5,7,13,14]. The case against applying automation wherever, whenever and at the highest levels technologically feasible has been harder to make. Much research has been devoted to showing the disadvantages of reduced human engagement in system control and problem solving characteristic of high-level automation [1,2,7,8,15-22]. These problems will be characterized next:

- 1) *Reduced Situation and System Awareness:* High levels of automation, particularly of decision-making functions, may reduce the operator’s awareness of system and environmental dynamics [23,24]. Humans tend to be less aware of changes when those changes are under the control of another agent (whether automation or human) than when they make the changes themselves [25]. Mode errors also illustrate the impact of automation on the user’s awareness of system characteristics [26,27]. Mode errors arise when the operator executes a function that is appropriate for a mode other than the one the system is currently in [28]. When a system is capable of automatically changing its mode, as is the case with aircraft Flight Management Systems (FMS), mode errors become more common precisely because the operator is less likely to be aware of the current system mode [26]. Several aviation incidents and accidents have involved this type of error [2,29].
- 2) *Trust, Complacency, and Over-Reliance:* Trust is an indicator of how accurately the operator understands the system [30,31]. Operators may not use well-designed, reliable automation if they believe it to be untrustworthy, or they may continue to rely on automation even when it malfunctions if they are overconfident in it. Highly automated systems are prey to both sorts of errors [7].

The problem of excessive trust or complacency has been documented in several studies showing that students in laboratory experiments [32], trained pilots in simulation [33], and experienced air traffic controllers using decision aiding automation [34] are poor at monitoring automation for occasional malfunctions if their attention is occupied with other tasks. In these studies, users grant more autonomy to a system than it was designed to support by almost always accepting recommendations even though they are sometimes incorrect. Over-reliance on automation can also manifest as a decision bias stemming from a heuristic to reduce the cognitive effort involved in solving a problem. This heuristic may result in “automation bias” [35] – a tendency to uncritically accept automation recommendations. Although reliance on automation may be an effective strategy in many cases, over-reliance can lead to errors when automation is less than perfect.

- 3) *Skill Degradation:* If higher levels of automation can result in complacency and loss of situation awareness, it is perhaps not surprising that they can also result in skill degradation if allowed to persist. The pilots of increasingly automated aircraft feared this effect with regards to psychomotor skills such as aircraft attitude control [2], but it has also been demonstrated for decision making skills [24]. In both cases, the use of an intermediate, lower level of automation alleviated skill degradation if the skills had been learned in the first place.
- 4) *Unbalanced Mental Workload:* Automation can sometimes produce extremes of workload, either too low or too high. That high levels of automation could leave an operator bored and inattentive is, perhaps, to be expected. That automation can increase workload, on the other hand, is one of the “ironies of automation” [8] because many automated systems are introduced as workload-saving moves, but this does not always occur. First, if automation is implemented in a “clumsy” manner, e.g., if executing an automated function requires extensive data entry or “re-programming” by human operators at times when they are very busy, workload reduction may not occur where it is most needed [36]. Second, if engagement of automation requires considerable “cognitive overhead” [37], i.e., extensive cognitive evaluation of the benefit of automation versus the cost of performing the task manually, then users may experience greater workload in using the automation.
- 5) *Degraded Overall Performance:* The most significant effect of using too high an automation level may be degraded overall performance of the human + machine system. In an experiment involving aircraft navigation and route planning, Layton et al. [38] provided operators with one of three levels of support ranging from ‘sketching only’, where the human sketched a desired route and the system provided feedback about its feasibility, to ‘full automation’ where the system automatically provided a recommended ‘best’ route according to its optimization criteria. An intermediate level allowed the user to ask for a route with specific characteristics that the system then provided if possible. They found that humans in the intermediate and high automation conditions frequently explored more routes because, in the highly manual sketching condition, the process of arriving at a route was too difficult to allow trying many alternatives consistently and fully. By contrast, as in [35], in the full automation condition, users tended to accept the first route suggested without exploring it or its alternatives deeply. Even when they did explore, the system’s recommendation tended to narrow and bias their search. Users tended to check the route provided for obvious mistakes rather than generating a preferred route on their own. Particularly in trials when the automation performed suboptimally (e.g., because it failed to adequately consider uncertainty in weather predictions), the intermediate level of automation produced better overall solutions.
- 6) *Lower User Acceptance:* Finally, an additional problem with high levels of automation is lack of user acceptance. This may be particularly true of highly trained and skilled operators of complex, high-criticality systems such as aircraft, military systems, process control, etc. For example, Miller [39], interviewed several pilots and designers to develop a consensus list of prioritized goals for a “good” cockpit configuration manager for the Rotorcraft Pilot’s Associate [40]. Even though this system provided advanced automation capable of managing information displays and cockpit functions to conform to pilot intent, two of the top three items on the pilots’ consensus list were “Pilot remains in charge of task allocation” and “Pilot remains in charge of information presented.”

Similarly, Vicente [41] and Bisantz et al. [42] cite examples of human interactions with even such low criticality automation as food planning aids in fast food restaurants, showing that operators can become frustrated when forced to interact with automation that removes their authority to do their jobs in the best way they see fit. Vicente [41] summarizes findings from [43] showing that jobs in

which human operators have high psychological demands coupled with low decision latitude (the ability to improvise and exploit one's skills for job performance) lead to higher incidences of heart disease, depression, pill consumption, and exhaustion.

7.5.2 Tradeoff Space for Effects of Automation Level

The findings summarized above show that a mixture of human and automation involvement is frequently desirable rather than the extremes of full or no automation. In these cases, human + machine systems must be designed for an appropriate relationship between operators and automation allowing both parties to share responsibility, authority and autonomy over many work behaviors in a safe, efficient and reliable fashion. The effects of different human-automation relationships over a task or function can be viewed as a 'tradeoff space'. Figure 7-8 presents a conceptual view of this space over three relevant parameters:

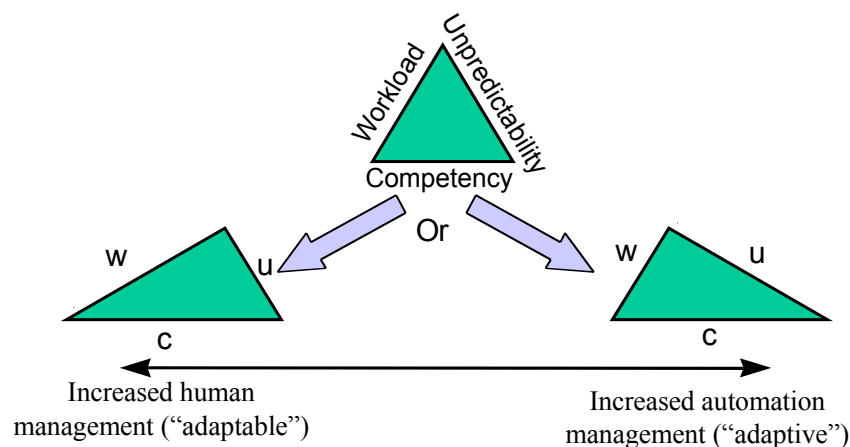


Figure 7-8: The Tradeoff Relationship between System Competency, Human Workload and Unpredictability.

The Competency of the Human-Machine System. Competency refers to correct behavior in context. Therefore, a system becomes more 'competent' whenever it provides correct behaviors more frequently or encompasses a greater number of contexts.

The Mental Workload Required for the Human to Interact with the System. Workload refers to the combined amount of attentional and cognitive "energy" the human must exert to use the system [44-46]. Mental workload for the human is modeled because it is the major constraint on the other two dimensions.

The Unpredictability of the System to the Human Operator. Unpredictability refers to the inability of the human to know exactly what the automation will do when. Unpredictability is a consequence of the human's not personally taking all actions in the system—of not being 'in control' directly and immediately. It is inversely correlated with situation awareness (at least awareness pertinent to automation functions) and, generally, workload. Good system and interface design and good hiring and training practices can serve to reduce unpredictability, but any form of task delegation—whether to automation or other humans—must result in a degree of unpredictability if it offloads tasks.

The triangle in Figure 7-8 illustrates the relationship, or 'tradeoff space', among these three dimensions. The performance of a set of functions to a given level of competency can only be achieved through some mix

of workload and unpredictability. A user's workload can be reduced by allocating some functions to automation, but only at the expense of increased unpredictability; conversely, reducing unpredictability by having the user perform functions increases workload. Alternate designs for a level of competency represent different mixes of workload and unpredictability – corresponding to varying the lengths of the triangle's sides while holding the base constant. It is sometimes possible to reduce both workload and unpredictability for a given level of competency through better design – corresponding to shortening the height of the triangle.

In this tradeoff model, any increase in human-machine system competency must affect the human in that either:

- 1) The added functionality must be fully controlled by the human(s), resulting in workload increases; or
- 2) It must be managed by automation, resulting in unpredictability increases.

Opperman [47] identified these alternatives as 'adaptive' and 'adaptable' approaches to system design (see also [48]). In either case, the human + machine system can adapt to various contexts, but in adaptive systems automation determines and executes the necessary adaptations, while in adaptable systems, the operator is in charge of the desired adaptations. The persistent debate (e.g., [49,50]) in the Human-Computer Interface community over intelligent agents vs. direct manipulation interfaces is a similar manifestation of these alternative approaches.

Another implication of the tradeoff space is that these approaches are the endpoints of a spectrum with many alternatives in between, each representing a different tradeoff between workload, unpredictability and competency (as in Figure 7-9). The range of alternatives available may be constrained by automation and/or human capabilities, but within the range of feasible systems, an alternative must be selected to assign roles and responsibilities between human(s) and automation. This decision is the process of selecting an automation 'level' or relationship and it corresponds to picking a point in the tradeoff space [1]. When the division of labor is done by a supervisor for a human team, the process may be called 'delegation'; when done by a designer prior to system operation, it is part of system design. Our objective is to provide a human supervisor the ability to flexibly delegate tasks to automation at the time of use rather than relying on a static design point.

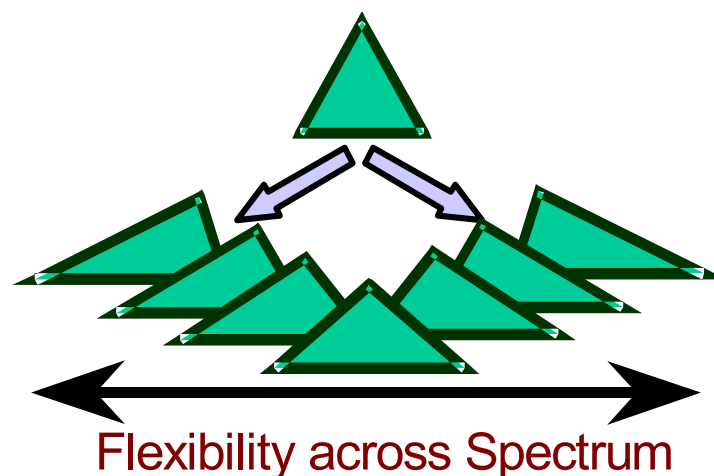


Figure 7-9: A Tasking Interface Provides Flexibility Within the Tradeoff Space.

7.5.2.1 Flexible Automation Levels

Traditionally, the chief difference between task delegation performed by a supervisor and design of an automated system has been that the supervisor had much more flexibility in what, when and how to delegate and better awareness of the task performance conditions, while the designer had to fix a relationship at design time and incorporate it statically into the to-be-built system for all contexts of use. More recently, “adaptive automation” [48,51-56], has been developed which chooses a level of automation for tasks based on contextual criteria such as location, situation, workload, experience, physiological state, etc. In adaptive systems, the division of labor between human and machine is not fixed. An adaptive aiding system may provide assistance through context-dependent forms of automation including the adaptive presentation of information.

The adaptive automation concept was proposed over 25 years ago [57], however the technologies for its effective implementation have only recently matured and empirical evidence of its effectiveness been provided. Studies have shown that adaptive systems can regulate operator workload and enhance performance, while preserving the benefits of automation [51,58,59]. The performance costs of certain forms of automation described previously – reduced situation awareness, complacency, skill degradation, etc – may also be mitigated [54,55,60-63]. Adaptive aiding systems have recently been successfully flight tested in the Rotorcraft Pilot’s Associate [64].

Such systems are truly “adaptive” in Opperman’s [47] sense since they choose the level of automation to apply. By contrast, human task delegation within a team is more nearly an “adaptable” system, since the human supervisor can choose which tasks to give to a subordinate, how much to dictate about how (or how not) to perform subtasks, how much attention to devote to monitoring, approving, reviewing and correcting task performance, etc.

The ability to delegate tasks to subordinates – and to do so flexibly, adapting both the tasks allocated and the degree of supervision, instruction and monitoring to the context and the capabilities of team members – is clearly a powerful form of organizing and performing work. It is also deeply familiar to anyone who has worked in a team or a supervisory setting. As described below, we have sought to extend such delegation capabilities to control over flexible automation. Before presenting that work, however, we must first describe what is meant by an automation level and then argue for an extension to traditional definitions to support delegation-based approaches to supervisory control.

7.5.2.2 Characterizing Automation Levels

To discuss alternative forms of automation, it is helpful to have a scheme for characterizing automation types, roles and responsibilities. In general, such characterizations have been made in terms of ‘levels’ of automation: defining a spectrum of possible relationships ranging from full human control authority to full automation.

7.5.2.3 Prior Automation Level Spectra

Bright [65] was perhaps the first to propose such a spectrum. Bright viewed automation as evolving through 17 levels of competency and noted that intermediate stages might well demand greater human workload, skill and training requirements than lower levels. Sheridan [66], is generally credited with defining “supervisory control” – a specific relationship where control automation allows the human to behave as if interacting with an intelligent, human subordinate. He described a ten point spectrum of automation levels whose endpoints are full control autonomy for the human (essentially no role for automation) and vice versa [66].

The intermediate levels in this spectrum, then, represent alternative forms of supervisory control interactions. A version of this list is shown in Table 7-5.

Table 7-5: Levels of Automation (after [66])

1	Human does it all
2	Computer offers alternatives
3	Computer narrows alternatives down to a few
4	Computer suggests a recommended alternative
5	Computer executes alternative if human approves
6	Computer executes alternative; human can veto
7	Computer executes alternative and informs human
8	Computer executes selected alternative and informs human only if asked
9	Computer executes selected alternative and informs human only if it decides to
10	Computer acts entirely autonomously

A problem with these simple, uni-dimensional models of human-automation relationships is that they are ambiguous about what the relationship is defined over. Parasuraman, Sheridan, and Wickens [1] recently noted that Sheridan's levels referred mainly to automation which makes decisions, offers suggestions and/or executes actions. There are, however, other jobs automation can do: for example, sensing and processing information to detect situations of interest. Parasuraman et al. [1] applied a four-stage model of human information processing to arrive at four functions that must be accomplished to perform most tasks:

- Information acquisition;
- Information analysis;
- Decision and action selection; and
- Action implementation.

Since these functions can be performed by either human or automation in various mixes, Parasuraman et al. [1] added a second dimension to Sheridan's spectrum. Most human + automation systems can be characterized by a mix of levels of automation across these four stages, as in Figure 7-10. One system (A) might be highly autonomous in information acquisition, but comparatively low on the other three functions, while a second system (B) might offer a high level of automation across all four sub-functions.

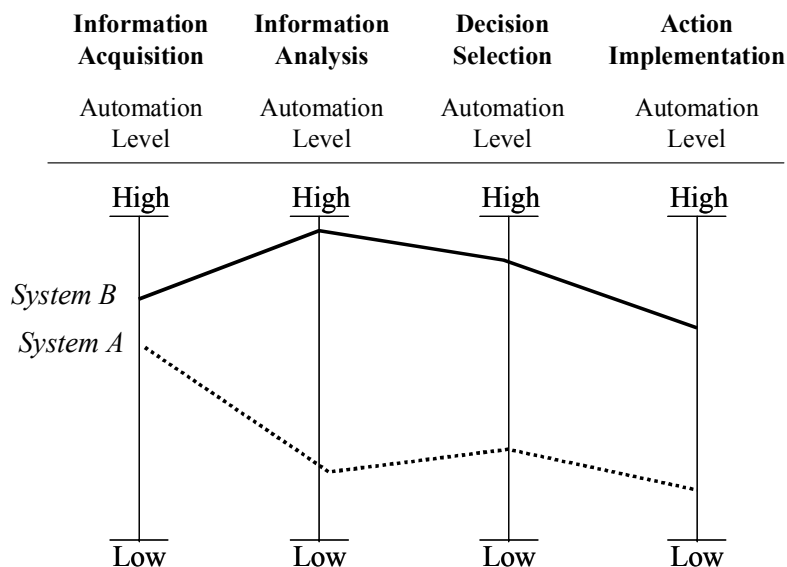


Figure 7-10: Levels of Automation by Information Processing Phase for Two Systems (from [1]).

7.5.2.4 Extending Automation Levels

An important implication of this two-dimensional, levels and stages model of automation [1] is that a parent task can be decomposed – at least into four stages – and that a single automation level need not be applied homogeneously. However, in this approach a parent task is decomposed into abstract subtasks based on information processing stages, whereas other task decomposition methods arguably provide more insight into how a task may be performed. Chief among these are functional decompositions (e.g., Operator Functional Modeling [67], Goals-Operations-Methods-Scripts (GOMS) models [68] and Plan Goal Graphs [69]) that stress the sub-functions required to achieve a parent, and sequential process models (e.g., PERT or CPM charts (e.g., [70], Petri nets [71]) that stress the temporal ordering and duration of a function’s steps. Such decompositions are inherently hierarchical and may proceed through any number of levels to some primitive, “stopping” level [72] that may be imposed by biology, physics or, more commonly, the functional purpose of the decomposition.

Thus, while the two-dimensional model of automation roles offered by Parasuraman et al. [1] represents a major advance over earlier uni-dimensional models, it arguably does not go far enough. The subdivision of a parent task into four information processing phases represents only a single level of decomposition into an abstract set of task categories. In practice, tasks are accomplished by hierarchical sequences of specific activities – the parent task’s subtasks. Automation may be applied differently to each and every subtask that comprises the parent task. Thus, the profile of automation levels sketched in Figure 7-10 should stretch not merely over the four information processing phases at one level of decomposition, but over as many subtasks and levels as we want or need to divide a parent task into.¹

¹ In fact, the relationship between automation level and task decomposition is more complex than this. As is well understood [1,2,10,26], automation does not merely shift responsibility for tasks but can change their nature as well. In a task decomposition, this means that some sub-tasks may be eliminated while others may be added. This implies that there will generally be multiple alternate decompositions of a parent task depending on, among other things, what level of automation is used. Each alternative constitutes a different combination of human and automation subtasks. The particular set represented should be a function of the model’s purpose: if used for design, the full set of possible and reasonable alternatives should be explored; if used to represent possible actions in an existing system, then only the available methods need be represented.

When one identifies a level of automation for a system using Bright's or Sheridan's spectra, one is identifying something like an average or modal level over the subtasks the system accomplishes. Similarly, when one uses a model of levels and stages of automation [1], one is clustering the subtasks by information processing stage and again averaging. Assigning levels by stages offers more sensitivity than assigning them only to the parent task, but it is still an abstraction. In practice, one could identify the *specific* subtasks to be performed and represent an automation level for each of them.

Why would one want to? More sub-tasks are not necessarily better and, in fact, Parasuraman et al. [1] explicitly chose a four-stage model over more elaborate alternatives to simplify design considerations. Precision in representation may be inherently desirable for some purposes (such as training and detailed design), but our interest is in supporting flexible task delegation with automation. As we saw above, for any intermediate level of automation for a task, there are roles for both humans and automation on its sub-tasks. Yet, *someone must coordinate those roles*. Insofar as the human is required to manage, or at least be aware of, that division of labor, s/he must understand the decomposition of the task in question. Supervisory control is a process of task delegation and delegation requires task decomposition. Task decomposition seems to reflect the way humans delegate responsibilities to subordinates, and reason about task performance when receiving feedback [74]. Delegation is, in short, a process of assigning specific roles and responsibilities for the subtasks of a parent task for which the delegating agent retains authority (and responsibility). Furthermore, communication about intent to the agent's subordinates is frequently in terms of specific goals, methods and/or constraints on how, when and with what resources the subtasks should be accomplished [73-75]. For these reasons, it is essential that those subtasks be modeled explicitly.

7.5.2.5 Using Extended Automation Levels in Design

Above, we argued that an automation level is a defined combination of roles and responsibilities between human and automation for a task to be performed, and that a task can generally be decomposed into subtasks – each of which may have its own automation level. This realization opens the doors for more explicit communication, either during design or operations, about the relationship between human and automation concerning the tasks to be accomplished.

We are developing a method for pushing this communication into the run-time environment – more closely emulating delegation in human-human work relationships and allowing the operator to smoothly adjust the 'amount' and level of automation used depending on such variables as time available, workload, decisions criticality, trust, etc.

While this does not eliminate the tradeoff presented in Figure 7-8, it mitigates it by allowing operators to choose various points on the spectrum for interaction with automation (Figure 7-9). The fundamental tradeoff remains, but the operator is in charge of choosing a tradeoff point in that space. This strategy follows both Rasmussen's [76] and Vicente's [41] approach of allowing the operator to 'finish the design' at the time and in the context of use. This allows more control and authority over how and when the user interacts with automation.

Such a system must avoid two problems. First, it must make achievable the task of commanding automation to behave as desired without excessive workload. Second, it must ensure safe and effective overall behavior. We have created a design metaphor and system architecture that addresses these two concerns. We call the general class of systems that can take delegation instruction at various levels tasking interfaces, because they allow posing a task to automation in the different ways one might 'task' a knowledgeable subordinate. Examples we would label tasking interfaces can be found in [75,77]. Our particular approach to enabling,

facilitating and ensuring correctness from a tasking interface, we call a Playbook – because it is based on the metaphor of a sports team’s book of approved plays. We have been exploring alternate methods to achieve the flexibility and ease of human-human delegation within human-machine systems. Two examples of our work on delegation systems – a “Playbook®” for task- and constraint-based delegation and “Policy” interactions for setting high level priorities for automation – are discussed in the next section.

7.5.3 References

- [1] Parasuraman, R., Sheridan, T. and Wickens, C. (2000). “A Model for Types and Levels of Human Interaction with Automation,” *IEEE Trans. Syst., Man, Cybern. – Part A: Syst. and Hum.*, Vol. 30, pp. 286-297.
- [2] Billings, C. (1997). *Aviation Automation: The search for a human-centered approach*. Mahwah, NJ: Lawrence Erlbaum.
- [3] Parasuraman, R. and Mouloua, M. (Eds.) (1996). *Automation and Human Performance: Theory and Applications*. Mahwah, NJ: Erlbaum.
- [4] Sheridan, T. (2002). *Humans and automation*. Santa Monica and NY: Human Factors and Ergonomics Society & Wiley.
- [5] Reason, J. (1997). *Managing the risks of organizational accidents*. Aldershot, UK: Ashgate Publishing Ltd.
- [6] Casey, S. (1993). *Set Phasers on Stun*, Santa Barbara, CA: Aegean Publishing Company.
- [7] Parasuraman, R. and Riley, V. (1997). “Humans and automation: Use, misuse, disuse, abuse,” *Human Factors*, Vol. 39, pp. 230-253.
- [8] Bainbridge, L. (1983). “Ironies of automation,” *Automatica*, Vol. 19, pp. 775-779.
- [9] Sheridan, T. (1987). “Supervisory Control”. In: *Handbook of Human Factors*. G. Salvendy, Ed. New York: John Wiley & Sons, pp. 1244-1268.
- [10] Woods, D. (1996). “Decomposing automation: Apparent simplicity, real complexity”. In: *Automation and Human Performance: Theory and Applications*, R. Parasuraman and M. Mouloua, Eds., Mahwah, NJ: Erlbaum, pp. 1-16.
- [11] Perrow, C. (1984). *Normal Accidents: Living with high-risk technologies*. USA: Basic Books.
- [12] Reason, J. (1997). *Managing the risks of organizational accidents*. Ashgate Publishing Ltd.; Aldershot, UK.
- [13] Bright, J. (1955). “Does automation raise skill requirements?”, *Harvard Bus. Rev.*, Vol. 36, pp. 85-98.
- [14] Lorenz, B., Nocera, F., Rottger, S. and Parasuraman, R., “Human Interaction with automated fault management during simulated space flight operations: The role of information sampling activities,” To appear in *Aviation, Space and Environmental Medicine*.

- [15] Amalberti, R. (1999). "Automation in aviation: A human factors perspective". In: Handbook of aviation human factors, D. Garland, J. Wise and V. Hopkin, Eds., Mahwah, NJ: Erlbaum, pp. 173-192.
- [16] Lewis, M. (1998). "Designing for human-agent interaction," Artificial Intelligence Magazine, (Summer), pp. 67-78.
- [17] Rasmussen, J. (1986). Information processing and human-machine interaction. Amsterdam: North-Holland.
- [18] Sarter, N., Woods, D. and Billings, C. (1997). "Automation surprises". In: Handbook of human factors and ergonomics, 2nd ed., G. Salvendy, Ed. New York: Wiley, pp. 1926-1943.
- [19] Satchell, P. (1998). Innovation and automation, Aldershot, UK: Ashgate.
- [20] Sheridan, T. (1992). Telerobotics, automation, and supervisory control. Cambridge, MA: MIT Press.
- [21] Wickens, C., Mavor, A., Parasuraman, R. and McGee, J. (1998). The future of air traffic control: Human operators and automation. Washington DC: National Academy Press.
- [22] Wiener, E. and Curry, R. (1980). "Flight-deck automation: Promises and problems," Ergonomics, Vol. 23, pp. 995-1011.
- [23] Endsley, M. and Kiris, E. (1995). "The out-of-the-loop performance problem and level of control in automation," Human Factors, Vol. 37, pp. 381-394.
- [24] Kaber, D., Omal, E. and Endsley, M. (1999). "Level of automation effects on telerobot performance and human operator situation awareness and subjective workload". In: Automation Technology and Human Performance: Current research and Trends, M. Mouloua and R. Parasuraman, Eds., Mahwah, NJ; Erlbaum, pp. 165-170.
- [25] Wickens, C. (1994). "Designing for situation awareness and trust in automation". In: Proc. IFAC Conf. on Int. Syst. Eng., Baden-Baden, Germany, pp. 174-179.
- [26] Sarter, N. and Woods, D. (1995). "How in the world did we ever get into that mode? Mode error and awareness in supervisory control," Human Factors, Vol. 37(1), pp. 5-19.
- [27] Sarter, N. and Woods, D. (1994). "Pilot interaction with cockpit automation II: An experimental study of pilots' model and awareness of the flight management system," Int. Jour. of Av. Psych., Vol. 4, pp. 1-28.
- [28] Sarter, N., Woods, D. and Billings, C. (1997). "Automation Surprises". In: Hndbk. of Hum. Fact. and Erg., 2nd ed., G. Salvendy, Ed., New York: Wiley, pp. 1926-1943.
- [29] Parasuraman, R. and Byrne, E. (2002). "Automation and human performance in aviation". In: Principles and practice of aviation psychology, P. Tsang and M. Vidulich, Eds., Mahwah, NJ: Erlbaum.
- [30] Lee, J. and Moray, N. (1992). "Trust, control strategies, and allocation of function in human-machine systems," Ergonomics, Vol. 35, pp. 1243-1270.
- [31] Lee, J. and Moray, N. (1994). "Trust, self-confidence, and operators' adaptation to automation," Int. Jour. Hum.-Comp. Studies, Vol. 40, pp. 153-184.

- [32] Parasuraman, R., Molloy, R. and Singh, I. (1993). "Performance consequences of automation-induced 'complacency,'" *Int. Jour. of Av. Psych*, Vol. 3, pp. 1-23.
- [33] Riley, V. (1994). *Human Use of Automation*, unpublished dissertation, University of Minnesota.
- [34] Metzger, U. and Parasuraman, R. (2001). "The role of the air traffic controller in future air traffic management: An empirical study of active control versus passive monitoring," *Human Factors*, Vol. 43, pp. 519-528.
- [35] Mosier, K. and Skitka, L. (1996). "Human decision makers and automated decision aids: Made for each other?" In: R. Parasuraman and M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications*. Mahwah, NJ: Erlbaum, pp. 201-220.
- [36] Weiner, E. (1988). "Cockpit Automation". In: E. Weiner and D. Nagel, Eds., *Human Factors in Aviation*, San Diego: Academic, pp. 433-461.
- [37] Kirlik, A. (1993). "Modeling strategic behavior in human-automation interaction: Why an 'aid' can (and should) go unused," *Human Factors*, Vol. 35, pp. 221-242.
- [38] Layton, C., Smith, P. and McCoy, E. (1994). "Design of a cooperative problem solving system for en-route flight planning: An empirical evaluation," *Human Factors*, Vol. 36(1), pp. 94-119.
- [39] Miller, C. (1999). "Bridging the Information Transfer Gap: Measuring Goodness of Information Fit," *Jour. Visual Lang. and Comp.*, Vol. 10, pp. 523-558.
- [40] Colucci, F. (1995). "Rotorcraft Pilot's Associate Update: The Army's Largest Science and Technology Program," *Vertiflite*, March/April, pp. 16-20.
- [41] Vicente, K. (1999). *Cognitive work analysis: Towards safe, productive, and healthy computer-based work*. Mahwah, NJ; Erlbaum.
- [42] Bisantz, A., Cohen, S., Gravelle, M. and Wilson, K. (1996). "To cook or not to cook: A case study of decision aiding in quick-service restaurant environments," Georgia Institute of Technology, College of Computing, Atlanta, GA, Report No. GIT-CS-96/03.
- [43] Karasek, R. and Theorell, T. (1990). *Healthy work: Stress, productivity, and the reconstruction of working life*. New York; Basic Books.
- [44] Moray, N. (1979). *Mental workload*. New York: Plenum.
- [45] Parasuraman, R. and Hancock, P. (2001). Adaptive control of workload. In: P.A. Hancock and P.E. Desmond (Eds.) *Stress, workload, and fatigue*. Mahwah, NJ: Erlbaum, pp. 305-320.
- [46] Wickens, C.D. and Holland, J.G. (1999). *Engineering psychology and human performance*. New York: Longman.
- [47] Opperman, R. (1994). *Adaptive User Support*. Hillsdale, NJ; Erlbaum.

- [48] Scerbo, M. (1996). "Theoretical perspectives on adaptive automation". In: Automation & human performance: Theory & applications, R. Parasuraman and M. Mouloua, Eds. Mahwah, NJ: Erlbaum, pp. 37-63.
- [49] Maes, P. (1994). "Agents that Reduce Work and Information Overload," Comm. of ACM, Vol. 37(7), pp. 31-40.
- [50] Shneiderman, B. (1997). "Direct manipulation for comprehensible, predictable, and controllable user interfaces," Proc. of the ACM Int'l Wkshp on Intelligent User Interfaces, New York, NY, pp. 33-39.
- [51] Rouse, W. (1988). "Adaptive automation for human/computer control," Human Factors, Vol. 30, pp. 431-488.
- [52] Banks, S. and Lizza, C. (1991). "Pilot's Associate; A Cooperative Knowledge-Based System Application," IEEE Expert, Vol. 6(3), pp. 18-29.
- [53] Morrison, J. (1993). "The adaptive function allocation for intelligent cockpits (AFAIC) program: Interim research and guidelines for the application of adaptive automation," Naval Air Warfare Center Tech. Rep. #NAWCADWAR-93031-60.
- [54] Parasuraman, R., Mouloua, M. and Molloy, R. (1996). "Effects of adaptive task allocation on monitoring of automated systems," Human Factors, Vol. 38, pp. 665-679.
- [55] Scallen, S., Hancock, P. and Duley, J. (1995). "Pilot performance and preference for short cycles of automation in adaptive function allocation," Ap. Ergon., Vol. 26, pp. 397-403.
- [56] Miller, C. and Hannen, M. (1999). "The Rotorcraft Pilot's Associate: Design and evaluation of an intelligent user interface for cockpit information management," Knowledge Based Systems, Vol. 12, pp. 443-456.
- [57] Rouse, W. (1976). "Adaptive allocation of decision making responsibility between supervisor and computer". In: Monitoring behavior and supervisory control, T.B. Sheridan and G. Johanssen, Eds. New York: Plenum Press, pp. 221-230.
- [58] Hancock, P., Chignell, M. and Lowenthal, A. (1985). "An adaptive human-machine system," Proc. IEEE Conf. on Syst., Man and Cyber., Vol. 15, pp. 627-629.
- [59] Parasuraman, R., Bahri, T., Deaton, J., Morrison, J. and Barnes, M. (1992). Theory and design of adaptive automation in aviation systems. (Progress Report No. NAWCADWAR-92033-60). Warminster, PA: Naval Air Warfare Center.
- [60] Duley, J. and Parasuraman, R. (1999). "Adaptive information management in future air traffic control". In: Automation technology and human performance: Current research and trends, M. Scerbo and M. Mouloua, Eds., Mahwah, NJ: Erlbaum, pp. 86-90.
- [61] Hilburn, B., Jorna, P., Byrne, E. and Parasuraman, R. (1997). "The effect of adaptive air traffic control (ATC) decision aiding on controller mental workload". In: Human-automation interaction, M. Mouloua and J. Koonce, Eds., Mahwah, NJ: Erlbaum, pp. 84-91.

- [62] Kaber, D. and Riley, J. (1999). "Adaptive automation of a dynamic control task based on workload assessment through a secondary monitoring task". In: Automation technology and human performance: Current research and trends, M. Scerbo and M. Mouloua, Eds., Mahwah, NJ: Erlbaum, pp. 129-133.
- [63] Parasuraman, R. (1993). "Effects of adaptive function allocation on human performance". In: Human factors and advanced aviation technologies, D.J. Garland and J.A. Wise, Eds., Daytona Beach: Embry-Riddle Aeronautical University Press, pp. 147-157.
- [64] Dornheim, M. (1999). "Apache tests power of new cockpit tool," Av.Week & Space Tech., October 18, pp. 46-49.
- [65] Bright, J. (1958). "Does automation raise skill requirements?". Harvard Business Review, Vol. 36, July-August, pp. 85-98.
- [66] Sheridan, T. and Verplank, W. (1978). "Human and Computer control of undersea teleoperators," MIT Man-Machine Systems Laboratory, Cambridge, MA. Technical Report.
- [67] Mitchell, C. (1987). "GT-MSOCC: A domain for research on HCI and decision aiding in supervisory control systems," IEEE Trans. on Sys., Man and Cybern., Vol. 17(4), pp. 553-572.
- [68] Card, S., Moran, T. and Newell, A. (1983). The Psychology of Human Computer Interaction, Mahwah, NJ; Lawrence Erlbaum Associates.
- [69] Geddes, N. (1989). Understanding human operators' intentions in complex systems. Ph.D. Dissertation, Georgia Institute of Technology.
- [70] Martinich, J. (1996). Production and Operations Management: An Applied Modern Approach, New York; John Wiley.
- [71] Murata, T. (1989). "Petri Nets: Properties, Analysis and Applications," Proceedings of the IEEE, Vol. 77(4), pp. 541-580.
- [72] Diaper, D. (1989). Task Analysis for Human-Computer Interaction, Chichester, U, Ellis Horwood.
- [73] Shattuck, L. (1995). Communication of Intent in Distributed Supervisory Control Systems. Unpublished dissertation. The Ohio State University, Columbus, OH.
- [74] Klein, G. (1998). Sources of Power; How People Make Decisions. Cambridge, MA; MIT Press.
- [75] Jones, P. and Jasek, C. (1997). "Intelligent Support for Activity Management (ISAM): An architecture to support distributed supervisory control," IEEE Trans. on Sys. Man & Cyber. – Pt. A: Sys & Hum, Vol. 27, pp. 274-288.
- [76] Rasmussen, J. and Goodstein, P. (1987). "Decision support in supervisory control of high-risk industrial systems," Automatica, Vol. 23, pp. 663-671.
- [77] Pande, A. and Hayes, C. (2002). "Plan-Edit: An Interactive Critic for User Guided Generation of High Quality Manufacturing Setup Sequences", Submitted for inclusion in Proc. of ASME Int'l Mfg. Cong. & Exposition, Montreal, Canada.

7.6 DELEGATION ARCHITECTURES: PLAYBOOKS AND POLICY FOR KEEPING OPERATORS IN CHARGE

We argue that as Unmanned Military Vehicles become more intelligent and capable, and as we attempt to control more of them with fewer humans in the loop, we need to move toward a model of delegation of control rather than the direct control that characterizes current practice. We identify and describe five delegation methods which can serve as building blocks from which to compose complex and sensitive delegation systems: delegation through (1) providing *goals*, (2) providing full or partial *plans*, (3) providing *negative constraints*, (4) providing *positive constraints* or *stipulations*, and (5) providing priorities or value statements in the form of a *policy*. We then describe two implemented delegation architectures that illustrate the use of some of these delegation methods: a “playbook” interface for UAV mission planning and a “policy” interface for optimizing the use of battlefield communications resources.

7.6.1 UMV Control as Human-Automation Delegation

While Unmanned Military Vehicles (UMVs) hold the promise of radical change and improvement for a wide range of military applications they also pose a host of challenging problems. Chief among these is how to enable a human operator, who may well be heavily engaged in tasks of his or her own, to retain sufficient control over the UMV(s) to ensure safe, efficient and productive outcomes. This problem is, of course, magnified when the UMVs may be responsible for the lives of many soldiers or civilians, may be capable of unleashing lethal force on its own, and when a single human may be striving to control groups or even swarms of potentially autonomous and independent actors and may be concurrently engaged in other, high tempo and criticality tasks of his or her own.

Yet this problem is not completely novel. Humans have been striving to retain control and produce efficient outcomes via the behavior of other autonomous agents for millennia. It just so happens that those “agents” have been other humans. Not surprisingly, we have developed many useful methods for accomplishing these goals, each customized to a different domain or context of use. When we have some degree of managerial authority over another human actor and yet will not be directly commanding performance of every aspect of a task, we call the relationship (and the method of commanding task performance) *delegation*. Delegation allows the supervisor to set the agenda either broadly or specifically, but leaves some authority to the subordinate to decide exactly how to achieve the commands supplied by the supervisor. Thus, a delegation relationship between supervisor and subordinate has many requirements:

- 1) The supervisor retains overall responsibility for the outcome of work undertaken by the supervisor/subordinate team and retains the authority commensurate with that responsibility.
- 2) The supervisor has the capability to interact very flexibly and at multiple levels with the subordinate. When and if the supervisor wishes to provide detailed instructions, s/he can; when s/he wishes to provide only loose guidelines and leave detailed decision making up to the subordinate, s/he can do that as well – *within the constraints of the capabilities of the subordinate*.
- 3) To provide useful assistance within the work domain, the subordinate must have substantial knowledge about and capabilities within the domain. The greater these are, the greater the potential for the supervisor to offload tasks (including higher level decision making tasks) on the subordinate.
- 4) The supervisor must be aware of the subordinate’s capabilities and limitations and must either not task the subordinate beyond his/her abilities or must provide more explicit instructions and oversight when there is doubt about those abilities.

- 5) There must be a “language” or representation available for the supervisor to task and instruct the subordinate. This language must (a) be easy to use, (b) be adaptable to a variety of time and situational contexts, (c) afford discussing tasks, goals and constraints (as well as world and equipment states) directly (as first order objects), and (d) most importantly, be shared by both the supervisor and the subordinate(s).
- 6) The act of delegation will itself define a window or space of control authority within which the subordinate may act. This authority need not be complete (e.g., checking in with the supervisor before proceeding with specific actions or using some resources may be required), but the greater the authority, the greater the workload reduction on the supervisor.

Items 4 and 6 together imply that the space of control authority delegated to automation is flexible – that the supervisor can choose to delegate more or less “space,” and more or less authority within that space (that is, range of control options), to automation. Item 5 implies that the language available for delegation must make the task of delegating feasible and robust – enabling, for example, the provision of detailed instructions on how the supervisor wants a task to be performed or a simple statement of the desired goal outcome.

7.6.2 Types of Delegation

We have developed a variety of architectures within which to support human delegation interactions with automation. Of particular interest as a core enabling technology is the “language” or representation for delegation described in item #5 above. As Klein points out [1], without successfully sharing an understanding of the tasks, goals and objectives in a work domain, there can be no successful communication of intent between actors. We believe there are five kinds of delegation actions or delegation methods that should be supported within such a representation, as described in the Figure 7-11 below. Note that each method forms a building block and they can be combined into more effective and flexible composite delegation interactions. Note also that the subordinate has a specific responsibility in response to each method, as articulated in the table below:

Table 7-6: Supported Delegation Actions and Methods

Supervisor’s Delegation Action	Subordinate’s Responsibility
1. Stipulation of a goal to be achieved – where a goal is a desired (partial) state of the world.	Achieve the goal(s) if possible (via any means available), or report if incapable.
2. Stipulation of a plan to be performed – where a plan is a series of actions, perhaps with sequential or world state dependencies.	Follow the plan if possible (regardless of out-come) or report if incapable.
3. Provide constraints in the form of actions or states to be avoided.	Avoid those states or actions if possible, report if not.
4. Provide “stipulations” in the form of actions or states (i.e., sub-goals) to be achieved.	Achieve those states or perform those actions if possible, report if not.
5. Provide an “optimization function” or “policy” that enables the subordinate to make informed decisions about the desirability of various states and actions.	Work to optimize value within the “optimization function” or “policy”.

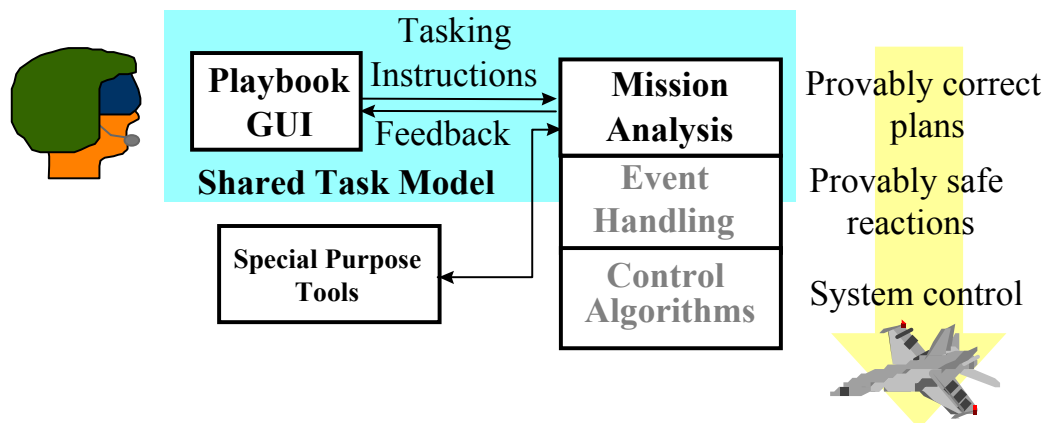


Figure 7-11: General Playbook Architecture.

In the remainder of this section, I will describe two delegation architectures we are developing. While neither system enables all of the types of delegation described above, and neither is fully implemented yet, collectively they illustrate the five types of delegation and provide a rich and highly flexible set of interactions for human-automation delegation.

7.6.2.1 Playbook – Delegation of Goals, Plans and Constraints

The first architecture is based on the metaphor of a sports team’s playbook. A playbook works because it provides for rapid communication about goals and plans between a supervisor (e.g., a coach) and a group of intelligent actors (the players) who are given the authority to determine how to act within the constraints inherent in the coach’s play. Our Playbook architecture supports delegation action types 1 – 4 in principle and has been implemented in prior prototypes to include action types 2 and 4.

The basic Playbook system architecture is presented in Figure 7-8. The Playbook ‘proper’ consists of a User Interface (UI) and a constraint propagation planner known as the Mission Analysis Component (MAC) that communicate with each other and with the operator via a Shared Task Model. The operator communicates instructions in the form of desired goals, tasks, partial plans or constraints, via the UI, using the task structures of the shared task model. The MAC is an automated planning system that understands these instructions and (a) evaluates them for feasibility and/or (b) expands them to produce fully executable plans. The MAC may draw on special purpose planning tools (e.g., an optimizing path planner) to perform these functions, wrapping them in its task-sensitive environment. Outside of the tasking interface, but essential to its use, are two additional components. An Event Handling component, itself a reactive planning system capable of making momentary adjustments during execution, takes plans from the Playbook. These instructions are sent to control algorithms that actually effect behaviors.

Operator interaction with the Playbook can be via a variety of user interfaces customized to the needs of the domain and work environment, but operator commands are ultimately interpreted in terms of the Shared Task Model. To date, we have developed prototype playbooks for UCAV teams [2], and Tactical Mobile Robots [3], and are currently developing prototypes for the RoboFlag game [4] and for real-time interaction with teams of heterogeneous UMVs. Below, we provide a description of user interaction with one Playbook interface we developed with Honeywell Laboratories to illustrate the general concept.

HUMAN AUTOMATION INTEGRATION

We developed the playbook illustrated in Figure 7-12 to enable a human leader to create a full or partial mission plan for UCAVs. This initial work was intended as a ground-based tasking interface to be used for a priori mission planning, but current playbook work is exploring interface modifications to enable real-time and in-flight tasking and task performance monitoring as well.

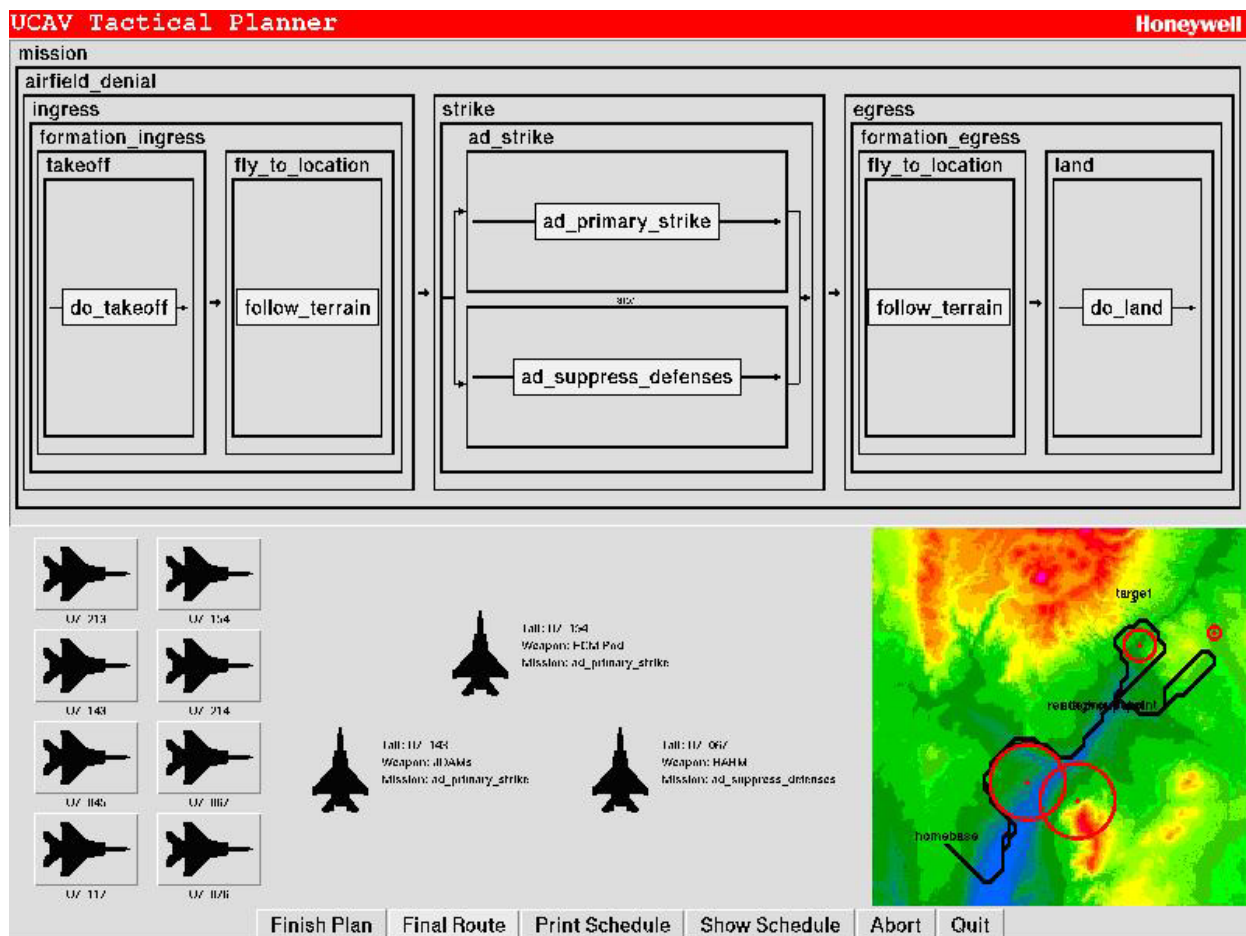


Figure 7-12: Prototype Playbook Interface for UCAV Mission Planning.

Figure 7-12 shows five primary regions of this Playbook UI. The upper half of the screen is a Mission Composition Space that shows the plan composed thus far. In this area, the operator can directly manipulate the tasks and constraints in the plan. The lower left corner of the interface is an Available Resource Space, currently presenting the set of aircraft available for use. The lower right corner contains an interactive Terrain Map of the area of interest, used to facilitate interactions with significant geographic information content. The space between these two lower windows (empty at startup) is a Resource in Use Space – once resources (e.g., UCAVs, munitions, etc.) are selected for use, they will be moved here where they can be interacted with in more detail. Finally, the lower set of control buttons is always present for interaction. This includes options such as “Finish Plan” for handing the partial plan off to the MAC for completion and/or review and “Show Schedule” for obtaining a Gantt chart timeline of the activities planned for each actor, etc.

At startup, the Mission Composition Space presents the three top-level plays (or ‘mission types’) the system currently knows about: Interdiction, Airfield Denial, and Suppress Enemy Air Defences (SEAD). The mission leader would interact with the playbook to, first; declare that the overall mission “play” for the day was, say, “Airfield Denial.” In principle, the user could define a new top-level play either by reference to existing play structures or completely from scratch, but this capability has not been implemented yet.

This action is an example of type 2 delegation – providing a specific task for subordinates to perform – but because this is a very high level task in a hierarchical task network, the supervisor has left a great deal of freedom to the subordinates (in this case, the MAC and the UAVs themselves) to determine exactly how an “Airfield Denial” mission is to be performed. If this were the only delegation information the supervisor provided, the subordinates would be obligated to do their best to perform that action (an Airfield Denial mission), but would have a great deal of authority as to how best to accomplish it.

At this point, having been told only that the task for the day is “Airfield Denial,” a team of trained pilots would have a very good general picture of the mission they would fly. Similarly, the tasking interface (via the Shared Task Model) knows that a typical airfield denial plan consists of ingress, attack and egress phases and that it may also contain a suppress air defence task before or in parallel with the attack task – but just as a leader instructing a human flight team could not leave the delegation instructions at a simple ‘Let’s do an Airfield Denial mission today,’ so the operator of the tasking interface is required to provide more information. Here, the human must provide four additional items: a target, a homebase, a staging and a rendezvous point. Each of these is a *stipulation*, or positive constraint, telling the subordinates that whatever specific plan they come up with to accomplish the higher level mission must include these attributes – and thus, they are examples of type 4 delegation interactions. Most of these activities are geographical in nature and users typically find it easier to perform them with reference to a terrain map. Hence, by selecting any of them from the pop up menu, the user enables direct interaction with the Terrain Map to designate an appropriate point. Since the Playbook knows what task and parameter the point is meant to indicate, appropriate semantics are preserved between user and system. As for all plans, the specific aircraft to be used may be selected by the user or left to the MAC. If the user wishes to make the selection, s/he views available aircraft in the Available Resource Space and chooses them by clicking and moving them to the Resources in Use Area.

The mission leader working with a team of human pilots could, if time, mission complexity or degree of trust made it desirable, hand the mission planning task off to the team members at this point. The playbook operator can do this as well, handing the task to the MAC via the “Finish Plan” button. The leader might wish, however, to provide substantially more detailed delegation instructions. S/he can do this by progressively interacting with the playbook UI to provide deeper layers of task selection, or to impose more stipulations on the resources to be used, waypoints to be flown, etc. For example, clicking on “Airfield Denial” produces a pop-up menu with options for the user to tell the MAC to “Plan this Task” (that is, develop a plan to accomplish it) or indicate that s/he will ‘Choose airfield denial’ as a task that s/he will flesh out further. The pop-up menu also contains a context-sensitive list of optional subtasks that the operator can choose to include under this task. This list is generated by the MAC with reference to the existing play structures in the play library, filtered for current feasibility.

After the user chooses ‘Airfield Denial’ the system knows, via the Shared Task Model, that this task must include an Ingress subtask (as illustrated in Figure 7-12). The supervisor does not have to tell intelligent subordinates this; it is a part of their shared knowledge of what an ‘Airfield Denial’ task means – and how it must be performed. To provide detailed instructions about how to perform the Ingress task, however, the user can choose it, producing a “generic” Ingress task template or “play”. This is not a default method of doing “Ingress”, but a generic, uninstantiated template – corresponding to what a human expert knows about what

constitutes an Ingress task and how it can or should be performed. A trained pilot knows that Ingress can be done either in formation or in dispersed mode and, in either case, must involve a “Take Off” subtask followed by one or more “Fly to Location” subtasks. Similarly, the user can select from available options (e.g., formation vs. dispersed Ingress, altitude constraints on takeoff, etc.) on context-sensitive, MAC-generated menus appropriate to each level of decomposition of the task model. One of our current challenges in creating Playbooks for real-time interactions is to enable them to be sensitive to the current state of affairs and of task performance so as to make intelligent assumptions about task performance possible – for example, if the supervisor wishes to command a currently airborne UAV, perhaps in a holding pattern, to perform an ‘Airfield Denial’ mission, both supervisor and subordinate should know that the Takeoff portion of an Ingress task is no longer necessary and should either be eliminated or be shown as already accomplished.

The user can continue to specify and instantiate tasks down to the “primitive” level where the sub-tasks are behaviors the control algorithms (see Figure 7-11) on board the aircraft can be relied upon to execute in flight. Alternatively, at any point after the initial selection of the top level mission task and its required parameters, the supervisor can hand the partly developed plan over to the MAC for completion and/or review. In extreme cases, a viable “Airfield Denial” plan for multiple aircraft could be created in our prototype with as few as five selections and more sophisticated planning capabilities could readily reduce this number further – but potentially more important, the operator (like a human supervisor dealing with intelligent subordinates) can also provide more detailed instructions whenever s/he deems them necessary or useful to performing the mission successfully and in the way s/he sees fit.

This Playbook illustrates delegation interactions 2 and 4 (plans and stipulations). The subordinates’ role in these types of interaction are described in the table above – to perform the plan through any set of sub-methods that adhere to the stipulations provided by the supervisor, or to report that this is infeasible. One of the MAC’s roles in the above example is to report when it is incapable of developing a viable plan within the constraints imposed, (e.g., if the user has stipulated distant targets that exceed aircraft fuel supplies). In a real-time delegation system, the MAC will be responsible for continual monitoring of performance to report when world states mean that plan performance is no longer capable of (or likely to) accomplish the user’s parent plan (e.g., because of equipment failures, adverse head winds, enemy countermeasures, etc.)

The Playbook architecture is, we believe, also capable of supporting delegation interaction types 1 and 3 (goals and negative constraints) as well. Supporting goal-based delegation interactions would require a slight modification to the shared task representation. Currently, we have used a representation that explicitly includes only hierarchically organized and sequenced tasks (i.e., actions to be performed). Tasks implicitly encode the goals they accomplish, but there are representations (such as Geddes Plan-Goal Graphs [5]) that explicitly interleave both plans and goals and a linked hierarchy. Use of such a representation, along with related modifications to the UI and MAC, would enable the supervisor to say, effectively, “Today we’re going to achieve a State” (e.g., the destruction of a given airfield) rather than or in addition to, the plan-based representation used above which allows only the issuing of task-based delegation commands (e.g., “Today we’re going to fly an airfield-denial mission”). The incorporation of negative constraints into the interaction (delegation interaction method #3), would require a less substantial modification to the Playbook architecture – potentially requiring only a UI addition to enable the supervisor to incorporate negative commands about task types and state parameters (e.g., “do NOT fly through this valley or use this type of munition”) and then requiring the MAC to create plans which avoid those negative constraints.

7.6.2.2 Policy – Delegation via Abstract Value Statements

The final type of delegation interaction offers the ability to provide priorities between alternate goals and states and to do so more abstractly than the above methods. Sometimes supervisors don’t have a single,

concrete world state goal in mind, much less a specific plan for accomplishing it. Sometimes supervisors must issue commands well in advance to cover a wide range of largely unanticipatable circumstances. In these cases, the delegation instructions will be less a specific statement of actions to take or world states to be sought or avoided, but rather a general statement of outcomes that would be more or less good or valuable (or, conversely, bad or to be avoided) than others. We refer to the set of such abstract value statements that a supervisor might provide as his or her “policy” for performance in the domain.

We have developed policy-based architectures for two applications: providing commanders’ guidance to a resource controller for battlefield network communications [6], and providing visualization and feedback to dispatchers in upset contexts in commercial aviation [7]. We will describe the first of these below.

A *policy statement* is an abstract, general, a priori statement of the relative importance or value of a goal state in the domain. In its simplest form, policy provides a method for human operators to mathematically define what constitutes “goodness” in terms of the outcomes of the delegation. Once defined, a policy statement can be treated as a rule and evaluated against a current or hypothetical context – if the rule is true in the context, then the context incurs the “goodness” (or badness) value stipulated by the rule. Alternate contexts (which could be tied to the expected outcomes of alternate decisions) can then be evaluated against each other by examining the set of policy rules that are satisfied or violated and the resulting set of goodness/badness values accrued. A set of individual policy statements can be bundled together, and these *policy bundles* can be used to flexibly define the priorities that apply in a given situation (priorities can change given different circumstances).

A policy-based delegation system requires at least three components:

- 1) A representation for specifying the “policy” in terms of the value of various partial world states;
- 2) A user interface for allowing one or more users to input their policies and, if desired, view results of policy application;
- 3) A computational framework that allows evaluation of a current situation or hypothetical proposed situation against the expressed policy; or
- 4) An engine that allows application of the policy either to the control of resource application or to a visualization of sensed data about a current situation or projected data about a future or simulated situation.

In the development of a policy-based delegation system for communications resource usage, we were striving to provide a means for commanders to tell an automated network management system their “policies” for how to prioritize the use of communications bandwidth in order to satisfy the most important requests most fully. Note, however, that “most important” was not a static concept, but rather changed across commanders and situations. For this application, we developed a policy representation that allowed commanders to assign, a priori and abstractly, a value to various kinds of communications requests. As communications requests then came in from various field units or operators, they could be matched against the commander’s policy statements and a value assigned to each of them. This value was then used by a resource optimizing controller to determine which requests should get network bandwidth with what priority.

This process is conceptually illustrated in Figure 7-13. Each commander’s policy is created as a set of statements each of which assigns an importance (or value) function to a defined sub-region in a multidimensional space. Regions might be based on a single dimension (‘Requests for weather information [Content] get Importance 0.2’) or on a combination of dimensions (‘Requests owned by the Zone Reconnaissance task [Owner] for weather information [Content] from Satellite 476B [Source] to 3rd Air Calvary Division [Destination]

HUMAN AUTOMATION INTEGRATION

get Importance 0.8). If the policy element regions are allowed to overlap, then they must be sequenced (typically from most to least specific) to indicate the order of precedence. In practice, the commander's policy is then used to assign an importance value to any incoming request for communication resources (illustrated conceptually in Figure 7-13). Each incoming request is matched against the sequenced series of policy element statements the commander has made. The first policy element that matches the request determines the importance of that request and informs an automated resource manager about the relative value of satisfying that request.

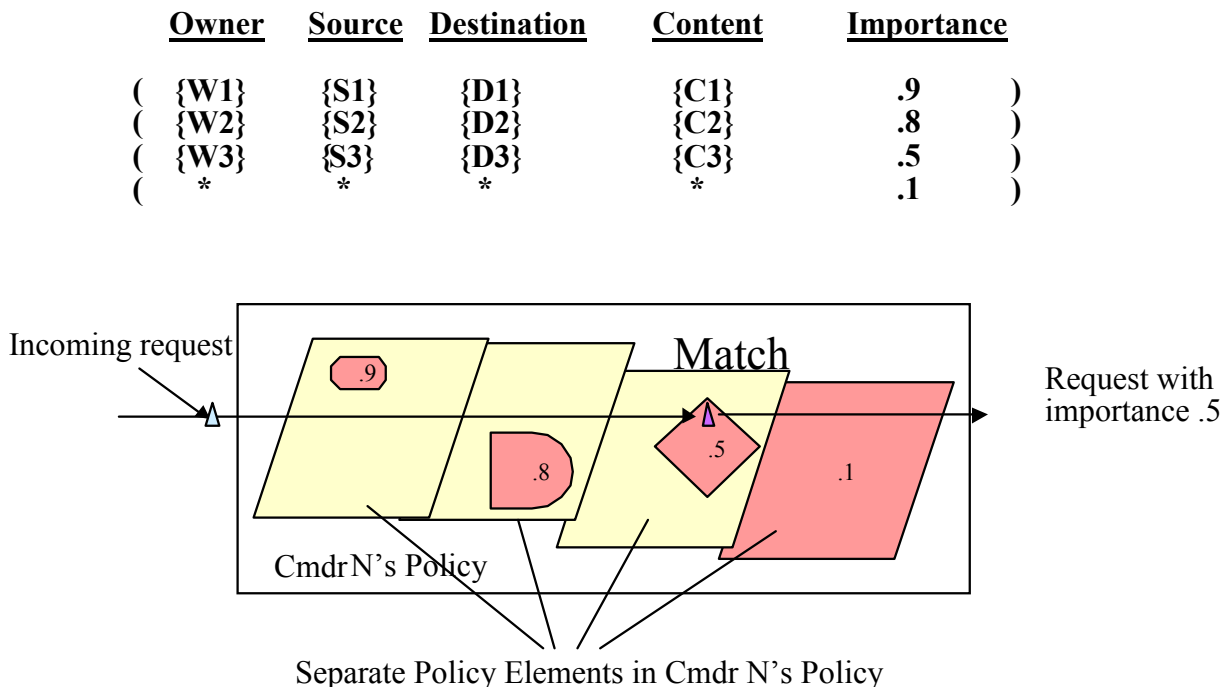


Figure 7-13: Representation of a Policy for Network Bandwidth Prioritization.

While conceptually simple, many useful functions can be performed within this framework. First, it is not necessary that importance be construed as an all-or-nothing value as it is depicted in 7-13. Instead, we have explored more sophisticated representations that allow the requestor to provide a description of how s/he wants the information requested along several dimensions (e.g., freshness, reliability, initiation-time, accuracy, resolution, scope, etc.) Then the resource management system can treat the importance value as a maximum number of value “points” to be awarded for satisfying the request perfectly, while still awarding itself points for partial satisfaction. This permits more sensitive management of resources to be performed.

Second, it is rarely the case that a single commander or supervisor is the only one who may have an interest in dictating policy about how subordinates behave. Rather, each commander must allocate his/her resources in accordance with the policies of those above. We support this requirement (Figure 7-14) by modeling policies that exist at nodes in a command hierarchy. As requests come in, they are matched against the commander's policy that governs them, but must then also be matched against his/her commander's policy – and so on, up the chain of command. We allow each commander to stipulate how this matching policy element should be resolved with the subordinate commander's matching policy element: as a ceiling or floor value, or linear combination of the values. Even when a single well-defined chain of command does not exist the policies of

different “interest groups” may be represented with relative weights on the importance values that each would assign to a potential outcome. We used this approach in representing the many, varied interests which impact the decisions of a commercial airline’s dispatch operators (e.g., crew scheduling, maintenance scheduling, marketing, passengers, finance, etc.) [7].

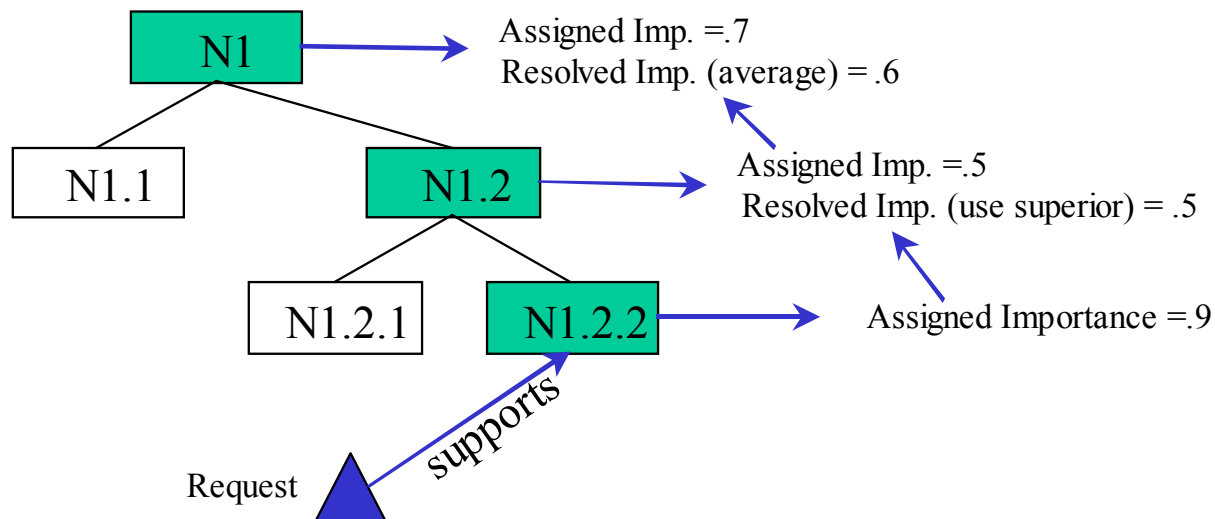


Figure 7-14: Cross Echelon Policy Application and Resolution.

Folding this policy-based form of delegation interaction (method 5) into an overall architecture that includes the other methods is not as difficult as it might first appear. While we have not yet developed a system that accomplishes this, the way forward is clear. Policy is simply an assignment of value or priority to the goal states and tasks in the other delegation interaction types. Priorities for resource usage and the desirability of various outcomes stem, after all, from a superior’s goals and plans for subordinates (whether human or machine). If, for example, I task a given unit under my command to perform an Airfield Denial task, and I know that their task is the most important of all concurrent tasks to me, then I have effectively said that giving them the resources they require to perform that task (specific aircraft, munitions, fuel, communications bandwidth, etc.) represents the highest value to me. In other words, delegation interactions that provide specific goals, plans, stipulations and constraints to subordinates carry with them specific policy implications. Whenever a commander can provide more specific delegation instructions, this will generally get him/her closer to the results desired from his/her subordinates, but this will not always be the case. Hence, the ability to stipulate more abstract policies should probably be preserved in a complete delegation system as a means of covering unexpected and unfamiliar situations.

7.6.3 Conclusions and Future Work

While the work described above represents a general framework for delegation interactions suitable for human interaction with smart automation of various kinds and, perhaps uniquely, suitable for the tasking of multiple UMVs, our work has thus far progressed only to the proof of concept stage. As noted above, we have currently implemented only portions of the various methods of delegation that a fully flexible delegation interface might benefit from, and have done so in disparate systems. Furthermore, our proof of concept implementations have not yet afforded us the opportunity to do rigorous human in the loop evaluations to demonstrate improved performance, if any.

These situations are changing, however. We are currently engaged in exploration of human interaction with Playbook-like interfaces with Parasuraman and Galster [4] and are beginning work on a Playbook interface for real-time interactions with heterogeneous UMV assets by operators who may be concurrently involved in other critical tasks (under a DARPA-IXO SBIR grant). One of the goals of this work will be to develop task libraries and task construction tools and interface concepts to move the delegation interface work along toward implementation and utility.

Of course, anyone who has worked with a poorly trained, or simply mismatched, subordinate is well aware that it is possible for delegation to cause more work than it saves. Our challenge, and that of others who adopt a delegation framework for human interaction with complex and largely autonomous automation, will be to ensure that this does not happen – through judicious use of technology and substantial usability analysis and testing. On the positive side, however, we benefit from the knowledge that delegation approaches to interaction with intelligent yet subordinate actors have worked repeatedly throughout history and, particularly, the history of warfare. As automation in the form of UMVs increasingly takes its place as one of those actors we want to be intelligent, capable and effective yet remain subordinate, we will increasingly need methods for enabling *it* to interact with *us* in the ways that we trust and are familiar with. Since delegation is the primary method we have evolved to meet these requirements, it only makes sense to pursue delegation approaches to human interaction with automation.

7.6.4 Acknowledgements

Many people have contributed to the ideas presented above. A partial list includes Robert Goldman, Harry Funk, Michael Pelican, Dave Musliner, Karen Haigh, Michael Dorneich, Stephen Whitlow, John Allen, and Jim Richardson.

7.6.5 References

- [1] Klein, G. (1998). Sources of Power: How People Make Decisions. Cambridge, MA; MIT Press.
- [2] Miller, C., Pelican, M. and Goldman, R. (2000). “Tasking” Interfaces for Flexible Interaction with Automation: Keeping the Operator in Control. In: Proceedings of the Conference on Human Interaction with Complex Systems. Urbana-Champaign, Ill. May.
- [3] Goldman, R.P., Haigh, K., Musliner, D. and Pelican, M. (2000). MACBeth; A Multi-Agent, Constraint-based Planner. In: Notes of the AAAI Workshop on Constraints and AI Planning, Austin, TX, pp. 1-7.
- [4] Parasuraman, R., Galster, S. and Miller, C. (2003). Human Control of Multiple Robots in the RoboFlag Simulation Environment. To appear in Proceedings of the 2003 Meeting of the IEEE Systems, Man and Cybernetics society. October 5-8; Washington, DC.
- [5] Sewell, D. and Geddes, N. (1990). A plan and goal based method for computer-human system design. In: D. Diaper (Ed.) Human-Computer Interaction – INTERACT ‘90. Elsevier Science; North-Holland. pp. 283-288.
- [6] Funk, H., Miller, C., Johnson, C. and Richardson, J. (2000). Applying Intent-Sensitive Policy to Automated Resource Allocation: Command, Communication and Most Importantly, Control. In: Proceedings of the Conference on Human Interaction with Complex Systems. Urbana-Champaign, Ill. May.

- [7] Dorneich, M.C., Whitlow, S.D., Miller, C.A. and Allen, J.A. (2004). "A Superior Tool for Airline Operations," *Ergonomics in Design*, 12(2). 18-23. Dorneich, M.C., Whitlow, S.D., Miller, C.A. and Allen, J.A. (Submitted). A Decision-Support Tool for Airline Operation's Diversion Management. Submitted to *Ergonomics in Design*.

7.7 MODELLING MULTI-LAYERED CONTROL: APPLICATION OF THE EXTENDED CONTROL MODEL TO THE ANALYSIS OF UAV SCENARIOS

Automation has often been approached from the bottom up, starting with the system components. This has focused the issues on the merits of humans and machines either as a comparison of attributes and capabilities, or in terms of relative roles as in levels of automation. An alternative is to approach the problem from the top down, using the requirements to joint system performance as a starting point. In this approach the emphasis is on being in control. The controlling system must match the requisite variety of processes involving subsystems with different dynamics, degrees of complexity, and predictability. This requires multiple, simultaneous layers of control. A multi-layered control model provides a good basis for understanding the consequences of automation and the needs of various types of information to support views of the past, present, and future. The top down approach is illustrated by describing the four layers needed to control a vehicle.

The objective of this note is to demonstrate how an UAV scenario can be described using the principles of the Extended Control Model (ECOM). This in turn requires a discussion of the Autonomous Control Level (ACL) framework, which provides a common reference for work on UAVs relating to issues of automation and human factors. This report comprises three parts: a brief introduction to the ECOM, a discussion of the ACL framework, and a description of an UAV scenario using the ECOM as a frame of reference.

7.7.1 Introduction

This chapter considers how to approach the problem of controlling one or more UAVs² to accomplish a given mission. This is a problem that is found in military as well as civilian domains, although it is the former that provides the context here. The issue is basically how to define and achieve an effective balance between manual and automatic control, i.e., between having an operator guide the vehicle and having the vehicle guide itself. This issue brings to the fore many of the problems that have been dealt with in the field of industrial automation, but also adds new perspectives and demands.

The chapter first presents a general framework for how to describe this problem, based on the principles of cognitive systems engineering. It then illustrates the principles of the description by considering an example taken from the military domain. The emphasis of the chapter is to present a methodological approach that can be used to make the problems tractable and, hopefully, solvable.

7.7.1.1 Control as a Cognitive Engineering Problem

With the possible exception of a few, unique cases the practical need to control something – a process, a vehicle, or a socio-technical system – always faces two predicaments. One is that control invariably takes place in time and requires time: processes are dynamic and developments are only incompletely predictable. The other is that usually more than one activity is going on, which means that more than one line of development must be kept keep track of. Even in cases where a controller can focus on a single process,

² The term UAV – for uninhabited aerial (or airborne) vehicle – is used as a general reference to unmanned vehicles, including land-based and sea-based versions.

that process may have to be considered with multiple time-horizons, hence effectively as being composed of multiple and potentially asynchronous processes.³

The consequence of this is that it is inadequate to address the control problem by methods that use decomposition as the main principle. Any system can structurally be described as being composed of a number of parts or subsystems, which in turn may be described as composed of parts or subsystems and so on, until the level of elementary components is reached.⁴ Yet while such descriptions are highly suitable for an instantiation of a system's structure, they are not necessarily the best way to describe a system's functions. Here it may be more appropriate to begin by understanding what systems do – or what they are supposed to do – rather than by describing what they are made of. Decomposition is a powerful analytical tool, which has become an almost sacred principle of Western science. Because of that it is too often taken for granted, which means that it sometimes is used when it should not have been. For instance, if we apply the notion of a human-machine system this already embraces the assumption that it is meaningful to make a distinction between humans and machines as two major groups of components. This assumption can, however, easily be questioned. It is, indeed, entirely possible to start an analysis from the notion of goals and means and use that as the guiding principle when a system description is developed. This is a well-established tradition as demonstrated by the classical work of Miller, Galanter and Pribram [1] although it often is disregarded by the mainstream of HCI and HMI.⁵

Discussions of how humans and machines can work together to the benefit of the overall human-machine system can, of course, not avoid the thorny issue of how functions should be allocated or distributed between the parts. Even if the starting point is a functional analysis, it is sooner or later necessary to consider how the resulting design should be implemented. Function allocation also implies that a certain level of automation exists, since without that machines would be incapable of functioning independently, hence to have functions assigned to them. Indeed, the word automation, which is a combination of the Greek words *auto-*, “self” and *-matos*, “willing”, means something that acts by itself or of itself. In the modern usage an artefact is said to be automatic if it is self-regulating or able to act or operate in a manner that is determined by the conditions, but which is essentially independent of external control.

To illustrate the differences in how humans and machines can work together, consider an automobile from the 1960s, such as an Austin Mini or a Volkswagen. In these cars very few things were automated – indeed, even the windshield wipers had to be stopped manually in the right position. For such cars there was therefore no need to consider function allocation or to worry about the relation between humans and automation. The driver had to do everything, specifically to control speed and direction while maintaining sufficient safety margins. The situation is completely different for a modern car. At the top of the range, cars are typically equipped with systems such as cruise control – or even adaptive cruise control, anti-locking brakes, electronic stability programs, traction control, and lane departure warnings as well a electronic climate control, automatic transmission, rain sensors, etc. The driver still has to control the direction and speed of the car – or at least to indicate the desired direction and speed, since in many cases the car can then take care of the rest. In short, the situation has changed completely, and the control needed to ensure safe driving is now distributed between the driver and a number of automated systems in the vehicle.⁶

³ It might be more correct to say that the operator focuses on only one goal. Any goal may be considered from different perspectives and using different criteria, hence require multiple processes to be achieved.

⁴ As the story of the atom shows, the level of elementary components is never absolute, but depends on the frame of reference.

⁵ The basic ‘component’ in this work was the Test-Operate-Test-Exit (TOTE) unit, which describes a pattern of activity rather than a structure.

⁶ Although the gradual transition of control from the driver to the vehicle always is done with the best of intentions, it sooner or later leads to unexpected problems of risk and responsibility.

From a historical perspective, automation has been used either to ensure a more precise performance of a given function or to improve the stability of system performance. After the industrial revolution, a further motivation was to increase the speed of work and production. The net effect of the increasing use of technology was that humans gradually came to be seen as a bottleneck for system performance, thereby strengthening the need of further automation. It is no coincidence that human factors engineering emerged in the late 1940s, when the rapid changes brought about by the scientific and technological developments in the preceding decade had undermined the hitherto peaceful co-existence between humans and machines. These developments opened the field for a new type of engineers, branded rather appropriately by Norbert Wiener as *gadget worshippers* [2, p. 53], defined as people who “regard(ed) with impatience the limitations of mankind, and in particular the limitation consisting in man’s undependability and unpredictability.” In addition to being seen as a bottleneck for system performance humans were also perceived as a source of unwanted variability that was a primary cause of incidents and accidents. According to the logic of this line of reasoning, it therefore made sense to replace humans by automation as far as possible. Unfortunately, this view has created many of the problems we face today.

7.7.1.2 Bottom-Up Function Allocation

As soon as function allocation was recognised to be a problem, methods or principles were proposed to solve it. Most of these started from the bottom up, i.e., from the components and functions that were seen as constituting the system. Humans and machines were regarded as two separate components with distinct functions, which in the case of humans typically were sensory-motor or mental (cognitive) functions. In a similar manner tasks were decomposed into subtasks and activities, and a component’s ability to carry out specific activities became the basis for function allocation and automation. This could be done either by focusing on the activities as such [3] or by comparing humans and machines function by function [4]. The underlying premise was that humans were needed for machines to work, and the problem was to ensure that this could be done in an effective manner – although from a technological rather than psychological perspective. (If humans were not needed for machines to work, the problem would obviously disappear. This condition can, however, only be achieved by fully automated systems.)

The reasons for using the bottom-up approach are not hard to find. Automation began by applying technology to take over relatively simple and well-defined functions, such as James Watt’s Governor that controlled the speed of the steam engine. As long as technology was employed to take care of isolated functions, it made perfect sense to consider these alone and to compare humans and machines in terms of their specific capabilities. Once the tradition had been successfully established it was, however, carried over to cases where it should have been used with greater care or not have been used at all. These are typically the cases where it is incorrect simply to decompose a system into its elements.

Common to all bottom-up approaches is that they provide an assessment of the system in terms of component characteristics, rather than in terms of the overall functioning. The best-known example is probably the Fitts list [4], which compares the capabilities of humans and machines by a fixed set of attributes. A more recent example is the scale used to describe degrees or *levels of automation* [5], which proposes different roles or areas of responsibility for humans and machines. Although the direct purpose is to describe – and appraise – the resulting system, rather than to support function allocation the starting point is nevertheless the same: humans and machines seen as separate entities that can be compared by means of a common feature – in this case the degree of autonomy. The description is thus one of *how much* humans and machines do relative to each other, rather than of *what* they do. Since the various possible outcomes furthermore are considered to have different values, this evaluation serves indirectly as a guideline for function allocation. This aspect is even more noticeable in a later version of the scale, cf. Sheridan [6].

7.7.1.3 Top-Down Function Allocation

The alternative to a bottom-up approach is to begin from the top down by considering the requirements to the performance of the overall system. An example of that is the concept of critical functions [7], which has been used for design of displays and operational support in nuclear power plants. While critical functions are common to all systems they differ widely among domains. For instance, maintaining lift is a critical function in aviation, whereas in nuclear power production it is essential to maintain cooling inventory. Two well-known examples of top-down analysis in the behavioural sciences are the General Problem Solver [8] and the previously mentioned Test-Operator-Test-Exit (TOTE) operator [1]. They both represent the more general principle of goals-means analysis.

Although it is possible to define a set of general functions that apply to any system [9], it is sufficient for the present discussion to consider just one function, namely that of maintaining control. This, of course, requires a clarification of “who” is in control of “what”. The “what” is usually a dynamic process, i.e., something that is capable of continuous and spontaneous change, activity, or progress.⁷ In a similar manner, the “who” refers to the controller or the controlling system. Both process and controller are systems, which means that they can be described as “a set of objects together with relationships between the objects and between their attributes” [10, p. 81]. Since humans are cognitive systems [11,12], and since the controlling system is assumed to comprise both humans and technology, it is here referred to as a joint cognitive system (JCS).

To define the meaning of being in control, it is useful to start by noting how being out of control generally is associated with the occurrence of unwanted conditions. Being in control consequently means having the power or ability to direct and manage the development of events, while not being in control means that this ability is temporarily or permanently lost. A joint system is defined as being in control of a situation either if unexpected conditions do not arise, or if it is possible to avoid unwanted outcomes of such conditions. The former means that the joint system is able to prevent unexpected conditions from occurring; the latter means that the joint system is able effectively to recover from such conditions, should they occur.

In the top-down view, the objective of function allocation is to ensure that control is maintained. It is therefore necessary to consider the effects of function allocation – and of automation – for a variety of conditions over time, rather than for a pre-defined set of steady conditions. It is also necessary to consider which functions are required to maintain control and how they depend upon and support each other, rather than how they compare to each other on specific attributes of humans and machines. The structurally based distinction between system parts, such as humans and machines, is in this way replaced by a differentiation among the functions needed to achieve the overall system objectives.

7.7.1.4 Layers of Control

Depending on the domain, being in control can mean to arrive at a specific destination at a given time, to deliver something at a given place – and also at a certain time, to keep the value of selected process parameters within a certain range, etc. For some processes, such as heating a room or maintaining the water level in a vessel, control is usually uncomplicated and can be accomplished by a simple feedback loop. Most processes, however, comprise several functions or subsystems. The room may, for instance, be part of a larger building complex or a special facility, and the vessel may be a storage tank in a power plant. In these cases the control of a single function is just part of controlling the overall system. Subsystems may have different dynamics (rate of change or rate of response), they may differ in degree of complexity and

⁷ It is important to keep in mind that the term process can refer to either a physical, a mental, or a social process. The system can thus be a technological artefact, a human being, or an organisation.

predictability, and specific relations or dependencies may exist among them (cf. the definition of a system given above). Yet effective control must be able to consider all these differences.

This requirement is consistent with the Law of Requisite Variety. The simplest, and perhaps best known, formulation of this is also the title of a seminal paper on the subject: “Every good regulator of a system must be a model of that system” [13]. This basically means that an effective regulator or controller of a system – or a process – must be capable of responding to any situation that can possibly occur. In relation to controlling a vehicle, for instance, it means that the controller must be able to compensate for all disturbances and events such that the vehicle is kept within the envelope of safe and efficient performance.

7.7.1.5 Control and Models

The Law of Requisite Variety is generally interpreted to mean that the controller must have a sufficiently powerful model of the system being controlled. This tradition is especially strong in the field of human-machine studies, where the operator’s (mental) model has become a *sine qua non*. The Law of Requisite Variety nevertheless does not say that the regulator or controller must **have** a model of the system, but only that it must **be** a model of the system [14]. The difference between the two interpretations is important and has wide-ranging consequences. In the conventional way of thinking about models the unspoken assumption is that there must be both a model of what needs to be known about the process, and a “mechanism” of some sort to execute or interpret the model. This convention has been established by artificial intelligence and knowledge-based systems (cf. the notion of an inference engine in expert systems), and is possibly a rudiment from Aristotelian logic. The need to keep models and mechanisms separate and distinct is, however, a convention rather than a law of nature. In other words, the variety that the controller must have (to match the requisite variety) need not be represented explicitly by a model or a formal representation, but can be a feature of how the controller functions as such – specifically that the controller can respond adequately to every possible situation.

In the field of human-machine studies, systems that need to be controlled are usually complex and comprise multiple processes that develop with different speeds and which therefore must be described by different time frames. In the example of maintaining the water level in a storage tank, the time frame for that (sub)process is different from the time frame of power production. Filling or emptying a tank is a matter of minutes, rather than hours while power production is a process that develops more slowly, and which must be considered in a time frame of hours or days. The control of the overall process (power production) thus differs from the control of the water level in the tank. The complexity (requisite variety) that this creates must be matched by the controller, which therefore in some important sense must mimic the essential features of the process.

7.7.1.6 Requisite Variety as Layers of Control

As a generic example, consider the control of a transportation process, such as driving a car from home to work or guiding an unmanned vehicle to a destination. In both cases it involves the movement of a vehicle between two points, A and B. To achieve this it is necessary to control the overall progress of the vehicle, i.e., to ensure that it gets nearer to B – which is not always the same as getting further from A. It is also necessary to ensure that the vehicle steers clear of obstacles in the close environment, i.e., that it does not collide with any stationary or moving object, and that it negotiates changes in speed or direction in an effective manner. It is furthermore necessary to ensure that the vehicle has the necessary resources to move, e.g., power. It is finally necessary that the purpose of the transportation is defined, such as the locations of points A and B, the criteria for effective transportation (e.g., speed, power consumption, load, etc.).

In this example four layers of control were required. Other models have often suggested three different types of control, such as strategy, tactics, and operation [15], heading, pursuit, and pre-cognitive control [16], skill-based, rule-based, and knowledge-based performance [17], and strategical (planning), tactical (manoeuvring), and operational control [18]. The reason for proposing four layers rather than three is that for most activities the layer of (operational) control presupposes a further layer where actions are executed. For humans this is exemplified by what we do automatically, without thinking of it or paying attention to it. Examples are walking or running, using tools (as professionals do), maintaining a steady speed and position (in driving), etc. In most activities execution takes place so quickly that we are not aware of it before it has happened, since attention – in the sense of the act of becoming aware of something – requires a certain time.

According to the Law of Requisite Variety, the controller must be able to provide the several types of control listed above, regardless of what the actual number is. The simplest way of doing that is obviously to assume that the functioning of the controller is organised in different layers as well. In this manner the functional architecture of the controller embodies part of the variety needed to control the process, and the controlling system therefore to some extent is a model of the process. This obviously needs to be supplemented by representations of the specific characteristics of the domain, the context, and the situation. The process may also require that there multiple goals are pursued at each layer. The result is therefore multiple, simultaneous control functions organised in a number of layers.

7.7.2 Contextual Control Models (COCOM)

In the modelling of cognition, human or otherwise, a distinction can be made between procedural prototype and contextual control models. A procedural prototype model assumes that a pre-defined sequence of (elementary) actions or a procedural pattern exists, and that this represents a more natural way of doing things than others. In a situation, the expected next action can therefore be found by referring to the natural ordering of actions implied by the prototype. Although some steps may be bypassed by taking shortcuts, and although the procedural pattern may be applied recursively, the underlying sequence itself is treated as immutable.

A contextual control model, on the other hand, implies that actions are determined by the context rather than by an inherent sequential relation between them. In a situation, the next action is therefore determined by the current context and by the competence of the JCS (cf. below). If recurring patterns of actions are found, this can be ascribed to the characteristics of the environment rather than pre-programmed action sequences.

7.7.2.1 Dynamic Control – COCOM

Procedural prototype models are ubiquitous in human factors and behavioural sciences and examples are easy to find.⁸ An example of a contextual control model is provided by the COCOM, which describes how a controller or controlling system can maintain control of a dynamic process.⁹ In this model the basic principle is that decisions or ‘actions’ are determined by the current understanding of the situation (called ‘construct’, cf. Figure 7-15), which includes the anticipation or expectation of what will happen next. The ‘events’ represent the result of the actions (hence the feedback). If they match the expectations, they reinforce the ‘construct’; if there is a mismatch, the ‘construct’ must be modified. The ‘events’ can also be completely unexpected, for instance if they are due to disturbances; that, of course, also demands a modification of the

⁸ Typical examples are models of decision making or problem solving.

⁹ A more detailed description can be found in Hollnagel [19] and Hollnagel and Woods [12]. In the case of the COCOM, the generic and specific names are unfortunately identical.

‘construct’. The model can account for the dynamics of a situation, specifically the consequences of lack of time, and for the effects of different levels of control.

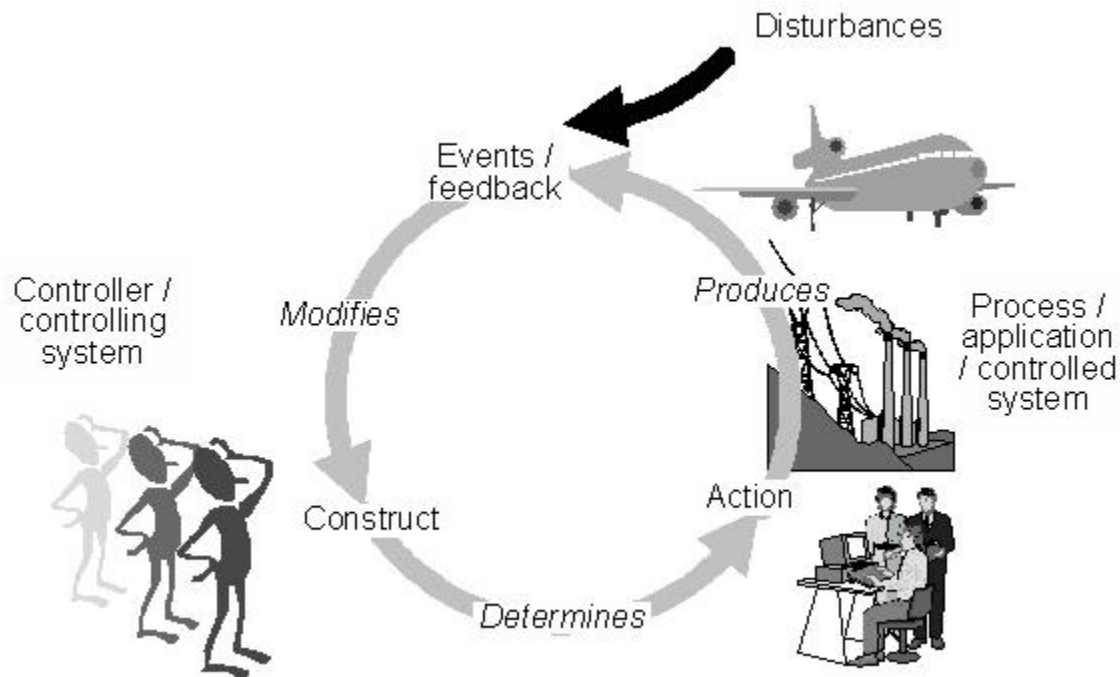


Figure 7-15: The Basic Construct-Action-Event Cycle.

7.7.2.2 Extended Control Model (ECOM)

The ECOM describes how the performance of a joint cognitive system (JCS) takes place on several layers of control simultaneously, using the notion of concurrent control loops. The ECOM follows the same principles of modelling as the COCOM [19] and is built on the latter in the sense that each layer corresponds to the fundamental construct-action-event cycle depicted in Figure 7-15. Some of these are closed (reactive), some are open (anticipatory), and some are mixed. The assumption of multiple layers of activity is crucial for the modelling approach, and it has in practice turned out that four layers are sufficient [20], although there is no accepted theory that determines their number. Although the ECOM has been developed to describe joint cognitive systems that include human operators, it has also been used to describe dynamic systems more generally, both technological and organisational. In the following sections, each of the four layers of activity will briefly be described, going from the lowest to the highest (cf. Figure 7-16).¹⁰

7.7.2.2.1 Tracking

The tracking layer of Figure 7-16 describes the activities required to keep a JCS inside predetermined performance boundaries, typically in terms of safety or efficiency. Activities at the tracking layer are very much a question of closed-loop control. For the skilled user such activities are performed automatically and therefore with little effort. While activities at the tracking layer usually are performed in an automatic and unattended manner, they may become attended, hence more like regulating, if conditions change.

¹⁰ A more extensive treatment can be found in Hollnagel and Woods [12].

HUMAN AUTOMATION INTEGRATION

In the ECOM, goals and criteria for activities at the tracking layer are provided by the regulating layer. Most of the tracking activities are readily amenable to technology take-over and automation. If done clumsily this may give rise to automation surprises because the almost complete take-over of closed-loop control makes it difficult for operators to follow what is going on, hence to maintain the situation comprehension that is needed at the other layers of activity.

7.7.2.2.2 *Regulating*

The regulating layer describes the activities by which a JCS achieves short-term goals, such as specific manoeuvres relative to the environment (which need not be physical space). Regulating is itself basically a closed-loop activity, although anticipatory control may also occur (e.g., [16]). Activities at the regulating layer do not always take place smoothly and automatically, but may require attention and effort. These activities in turn refer to specific plans and objectives that come from the monitoring layer.

Under some conditions, the regulating loop may suspend the tracking loop. It may, for instance, be more important to keep maintain integrity than to follow a path. This can also be expressed as a temporary suspension of one goal (following a path) to the advantage of another (maintaining integrity). Incompatibility between goals can be resolved by changing or adjusting plans.

7.7.2.2.3 *Monitoring*

Whereas activities at the regulating layer may lead to either direct actions or goals for the tracking layer, activities at the monitoring layer are mainly concerned with setting objectives and activating plans for actions. This can involve monitoring the condition of the vehicle, although this has in most cases been taken over by automation, or the monitoring the state of the environment.

In many domains a distinction between regulating (of position) and monitoring (of location) can be made, although space may not always be physical (or Euclidean). In a vehicle, other activities at the monitoring layer may be related to information sources. Although this is not monitoring of performance *per se*, it may affect the ability to perform, particularly if it is non-trivial. Monitoring does not directly influence location of the vehicle in the sense of closed-loop control and regulation, but rather is concerned with the state of a JCS relative to its environment.

7.7.2.2.4 *Targeting*

The last type of action occurs at the targeting or goal setting layer. An obvious kind of goal-setting is with regard to the destination. That goal may give rise to several subgoals and activities, some of which can be automated or supported. Other goals have to do with criteria for acceptable performance.

Goal-setting is distinctly an open-loop activity, and is implemented by a nontrivial set of actions that often covers an extended period of time. Assessing the change relative to the goal is not based on simple feedback, but rather on a loose assessment of the situation – for instance, proximity to target. When the assessment is done regularly it may be considered as being a part of monitoring and control. If the assessment is done irregularly, the trigger is usually some unknown factor, perhaps time, perhaps a pre-defined cue or landmark (physical or symbolic), perhaps a background ‘simulation’ or estimation of the general progress (like suddenly feeling uneasy).

Figure 7-16 shows the relations among the four layers in a simplified manner. To avoid graphical clutter, Figure 7-16 includes only the goal dependencies among the layers; other dependencies exist, for instance,

in the propagation of feedback or events. For the same reason each layer is represented only by one construct-action-event cycle, even though there normally will be several concurrent cycles or loops. The arrows at the right-hand side of Figure 7-16 indicate the relative weight of feedback and feedforward control for each layer.

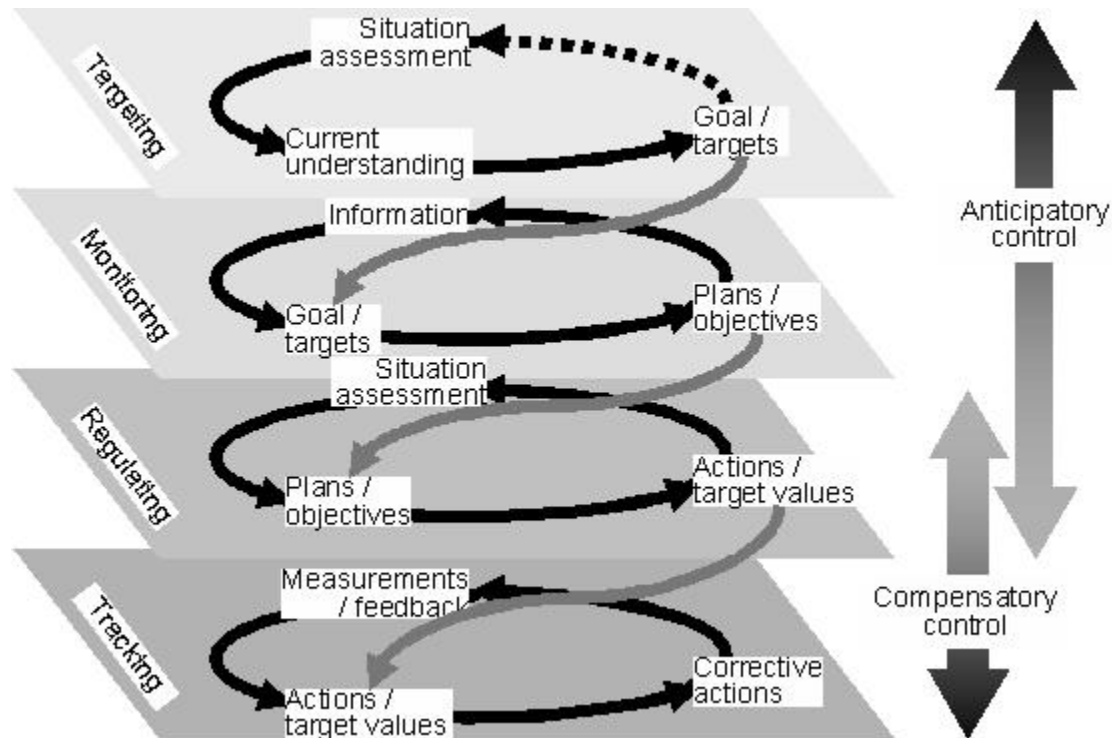


Figure 7-16: The Extended Control Model (ECOM).

7.7.2.3 ECOM Structure and Parameters

The main characteristics of each of the four layers are summarised in Table 7-7. This shows for each layer the type of control involved, the typical demands to attention in the case of a human controller, how often events can be expected to occur, and finally the typical duration of events. Here it is important to note that events on the tracking layer usually are of such short duration that in the case of humans they are pre-attentive. In other words, tracking-type behaviour is equivalent to skills, in the sense that it is something that is done more or less automatically and without attention. The regulating layer comprises actions of a short duration that do require attention, but not for long. The monitoring layer describes actions that go on intermittently as long as the task lasts, although the distribution can be decidedly irregular, depending on demands. Finally, actions on the targeting layer take place every now and then, almost always including the preparation of a task.

Table 7-7: Functional Characteristics of ECOM Layers

	Control Layer			
	Tracking	Regulating	Monitoring	Targeting
Type of control involved	Feedback	Feedforward and feedback	Feedback (condition monitoring)	Feedforward (goal setting)
Demands to attention	None (pre-attentive)	High (uncommon actions); low (common actions)	Low, intermittent	High, concentrated
Frequency	Continuous	Medium to high (context dependent)	Intermittent, but regular	Low (preparations, re-targeting)
Typical duration	< 1 sec ('instantaneous')	1 sec – 1 minute ('short term')	10 minutes – task duration ('long term')	Short (minutes)

The ECOM can be used to describe the interactions between the different layers. The assumption throughout is that all layers are active simultaneously, or rather that goals and objectives corresponding to different layers of control are being pursued simultaneously. One use of the ECOM is therefore to account for the nontrivial dependence between goals and activities among the layers, for instance when the tracking layer is interrupted by an unexpected disturbance. The goals of each control loop can also be temporarily suspended as when a higher-level goal is suspended in lieu of focusing on a lower level one. The bottom line is that controller performance and the effect of partial autonomy can be understood only in the context of the JCS as a whole, and not at the level of individual components or parts.

Returning to the issue of automation, it is clearly possible to consider the possibility of automation at each layer of control. In some cases functions have to be automated because it is impossible for humans to carry them out with sufficient speed, precision, or stability. In other cases functions have to be carried out by humans because the environment is too uncertain. In yet other cases there may be a choice. The top-down approach represented by the layers of control differs from the traditional way of comparing humans and machines because the comparison refers to the demands of the tasks rather than to the capabilities of system components. Table 7-7 can therefore also be used as a way of considering automation. In order to do this it is, however, necessary to enter into some other considerations.

7.7.3 Autonomous Control Level Framework

The concept of Autonomous Control Levels (ACL) has been developed to characterise issues of autonomous control in UAV missions. According to Huang et al. [21] the three main motivations for higher autonomy in unmanned system are:

- 1) Lack of bandwidth required for extensive tele-operation;
- 2) Safety for personnel; and
- 3) That mission effectiveness may be limited by cognitive workload, i.e., that humans are limited in their ability to perform their own tasks within the mission.

To that might be added time delays associated with communication links, which may hamper feedback control. A further motivation is that unmanned systems currently require control by one or more highly trained human operators; increasing the level of autonomy would clearly reduce this demand. All in all, increased autonomous control is seen as a way of maximising UAV utility.¹¹

7.7.3.1 Levels of Autonomy

The ACL framework comprises ten autonomous control levels are shown in Figure 7-17. While the labels for the different levels are evocative, it is difficult to find clear definitions of the terms, even in the Roadmap report [22]. In a discussion of the ACL, Reising [23] pointed out that the levels seemed to be based on a conglomeration of levels of automation, human information processing models, and adaptive automation. While attempts have been made to explain the ACL in terms of concepts such as automation, workload, situation awareness (e.g., [24], but see also [25]), Reising (*op. cit.*) pointed out that this, as well as the original proposal for the ten levels of automation [5], focused on the interaction *between* the operator and the UAV rather than on the autonomy of a vehicle or a JCS considered as a whole. The work of Kaber and Endsley [24] furthermore started from the levels of automation, hence did not provide an explanation of the nature of the levels nor their number. Knowing the development of descriptions of automation and autonomy it is, however, safe to assume that the reason for having ten levels can be found in 1978 proposal, which quickly achieved an almost mythical status – even though their number was later reduced to eight [6].

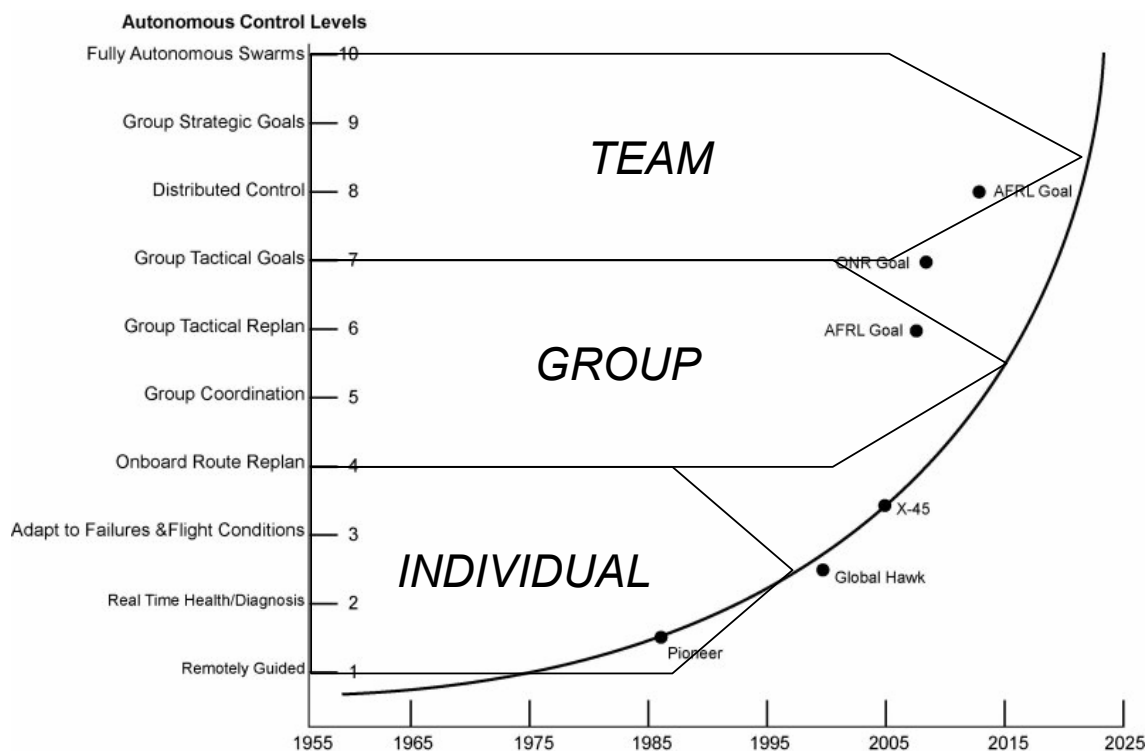


Figure 7-17: DOD UAV Roadmap 2000.

¹¹ In practice, the issue is one of automation rather than autonomy. An autonomous system is, by definition, completely independent, hence beyond human control. That is neither possible, nor desirable.

Figure 7-17 shows the ten levels of autonomy as developing gradually, beginning with remotely guided vehicles in the late 1950s and ending with fully autonomous swarms of vehicles in 2025.¹² Superimposed on this development is a characterisation of three mission types or configurations, namely individual (single vehicle), group (multiple vehicles), and team or swarm (multiple vehicles performing as a single entity). An important, but unspoken, assumption is that utility increases proportionally with the level of autonomy, hence that a high level of autonomy is more desirable than a low level. The ACL framework also implies bottom-up inheritance, i.e., that capabilities that exist at lower levels of autonomy are carried forth to higher levels.

7.7.3.2 Individuals, Groups, Swarms

In Figure 7-17, the three mission types – individual, group, and team (swarm) – are mapped as corresponding directly to increasing levels of autonomy. On further reflection, however, this need not be so.

As far as the three mission types are concerned, the meaning of an *individual* vehicle is obvious, i.e., it is a mission carried out by a single vehicle. The difference between *group* and *team*, where the latter is taken to be synonymous with *swarm*, is less obvious.¹³ As noted by Reising [23], a swarm does not appear to comprise a central controller that tells swarm what to do. As seen in the natural world – schools of fish, flocks of birds, swarms of bees – “... *swarming* itself is a type of emergent behavior, a behavior that isn’t explicitly programmed, but results as a natural interaction of multiple entities” [26, p. 1]. A swarm consists of a large number of members that all behave in a similar way, i.e., which have the same functions and capabilities. In particular, the members are replaceable.

On the other hand, a group is defined in social psychology as an assembly of individuals, recognised as being individually different, but treated, for some purpose, as parts of a larger unit. Group members usually have characteristic individual behaviours that in combination enable the group to achieve its purpose. The principal difference between a group and a team/swarm is consequently that group members can exhibit different (specialised) behaviours, while all members of a swarm behave in essentially the same way. In a group, the behaviour of the members must therefore be explicitly coordinated; in a swarm, the members behave collectively. Although the ‘intelligence’ of a swarm may be ‘emergent’, it does not necessarily mean that it is more difficult to control.

7.7.3.3 Mission Type and Autonomy

In the original for layers of automation [5], the end points of the scale were complete manual control and complete automation, respectively. In relation to the mission type, it is obvious that an individual vehicle can range from one extreme to the other, specifically that it in principle can be completely automated – but not completely autonomous. The same goes for swarms, although the manual control must address the swarm as a unit rather than the single entities that make up the swarm. In the case of a group, it is probably not feasible to consider manual control, since the coordination demands will be considerable and in a sense lead to the deconstruction of the group. On the other hand, there is nothing that, in principle, makes complete automation impossible. (A group might, in fact, be the only unit that can achieve autonomy.)

¹² The development is also shown as going faster and faster. This may be wishful thinking rather than reality.

¹³ Note, however, that the major groupings have no clear correspondence with the categories on the Y-axis. Levels 5-9 refer to the group, while only level 10 refers to the swarm.

These considerations suggest that the ACL should be considered in terms of the two dimensions of mission type and level of automation, rather than in terms of level of autonomy alone. The result of this exercise is shown in Table 7-8, where the level of automation simply is an ordinal number, with no inherent meaning.

Table 7-8: A Possible Two-Dimensional Description of Autonomous Control Levels

Level of Automation	Mission Type		
	Individual	Group	Team/Swarm
7	Strategic goals and replan	Strategic goals and replan	Strategic goals and replan
6	Tactical goals and replan	Tactical goals and replan	Tactical goals and replan
5	Onboard route replan (adapt to route changes)	Onboard route replan (adapt to route changes)	Onboard route replan (adapt to route changes)
4		Coordinated control	Collective control
3	Adapt to failure and flight conditions (“see-and-avoid”)	Adapt to failure and flight conditions (“see-and-avoid”)	Adapt to failure and flight conditions (“see-and-avoid”)
2	Real-time health / diagnosis	Real-time health / diagnosis	Real-time health / diagnosis
1	Manual control (remotely guided)		Manual control (remotely guided)

Although the distinction between strategic and tactical is firmly entrenched in military language, it is from a scientific point relative rather than absolute. The issue is basically one of defining the goals for the system under consideration, whether it is an individual UAV, a group or a team. If a target is set with a long *span-of-foresight* it corresponds to a strategy [15]; if, on the other hand a target is set with a short *span-of-foresight* and/or change frequently, it corresponds to a tactic. (In Shützenberger’s terms, “the optimal strategy is just the simple tactic of attempting to do one’s best on a purely local basis”.) The shortest span-of-foresight is in route revision, which therefore can be seen as a low-level tactic. For group missions, route revision requires coordination; for team/swarm missions, route revision can be achieved by collective control.

The ECOM described four layers of control called targeting, monitoring, regulating and tracking, respectively. If we consider the modified description of the ACL categories shown in Table 7-8, it is possible to propose a mapping between the ACL and the ECOM, as shown in Table 7-9. Here the two highest levels of autonomy – or rather, automation – are seen as corresponding to the targeting layer in the ECOM. The issue is one of defining the goals for the system under consideration, whether it is an individual UAV, a group or a team. It may well be that targeting capabilities will not be considered for individual missions.

Table 7-9: Relations between ECOM and the Revised ACL Description

ECOM Layer	Mission Type		
	Individual	Group	Team/Swarm
Targeting	Goal setting and replan (strategic, tactical)	Goal setting and replan (strategic, tactical)	Goal setting and replan (strategic, tactical)
	Onboard route replan (adapt to route changes)	Onboard route replan (adapt to route changes)	Onboard route replan (adapt to route changes)
Monitoring	Adapt to failure and flight conditions (“see-and-avoid”)	Adapt to failure and flight conditions (“see-and-avoid”)	Adapt to failure and flight conditions (“see-and-avoid”)
	Real-time health / diagnosis	Real-time health / diagnosis	Real-time health / diagnosis
Regulating		Coordinated control	Collective control
	Manual control (remotely guided)		Manual control (remotely guided)
Tracking			

The second part of the targeting layer is on-board route revision, i.e., the ability to generate or select an alternative route. The impetus to do that can come either from the monitoring of flight conditions or from an external source of command (a revision of strategic or tactical goals). Route revision is clearly relevant for single UAVs as well as for multiple UAVs. As regards multiple UAVs, the difference may be whether they are individually controlled (as in a group), or whether they are seen as a larger unit (e.g., a swarm), where individual behaviour is subsumed the behaviour of the swarm. In other words, in a group single UAVs may have different roles and responsibilities, whereas a swarm functions as a collective whole.) On the group level this corresponds to coordination and distributed control, on the team level to collective control.

The next ACL levels, real-time health/diagnosis and adapting to failures and flight conditions (“see-and-avoid”) correspond to the monitoring layer of the ECOM. Monitoring is clearly relevant for all three mission types. Indeed, autonomous monitoring is imperative for missions with multiple vehicles, since human monitoring of simultaneous activities is not reliable. Monitoring can be either of the vehicle itself or of the vehicle’s environment (threats).

As argued above, regulating – in the sense of manual control – is relevant mostly for the individual mission type. To do the same for a group of vehicles will require extensive coordination and therefore not be feasible. It may still be possible for a swarm, since that can be considered as one unit to be regulated. Even so, the efforts involved will not be the same as for an individual vehicle.

In Table 7-9, regulation occurs in two different meanings. In case of an individual vehicle, regulation corresponds to conventional remote guidance or manual control. In the case of groups and teams/swarms low level regulation of this type is not desirable. On the contrary, it is probably a precondition for group and team

missions to be possible that the control of basic manoeuvres is completely automated. There is, however, another level of regulation, which has to do with the proper coordination of group or team members. This coordination is required in order to be able to implement route changes quickly and efficiently, i.e., a sort of guidance at a higher level. In the case of groups and teams, both monitoring and regulating could be extensively automated, leaving targeting in the hands of human operators.

Finally the layer of tracking is assumed to be completely automated, as it already is today. For airborne vehicles tracking (roll, pitch, yaw) must happen so quickly that it exceeds human capability. This layer will therefore not be considered further here.

One consequence of the above considerations is that Figure 7-17 should be revised to show the three mission types in parallel relative to the control levels rather than in series.¹⁴ In other words, they represent three lines of development rather than one. There is, indeed, no good reason why a team should be seen as more difficult to automate than a group. In fact, it may well be the reverse, since a group requires the coordination of several individual behaviours rather than of a “single” behaviour of either an individual or a team/swarm seen as a “collective individual.”¹⁵ A suggestion of what this revision might look like is shown in Figure 7-18, which also reverses the ACL ordering of team and group.

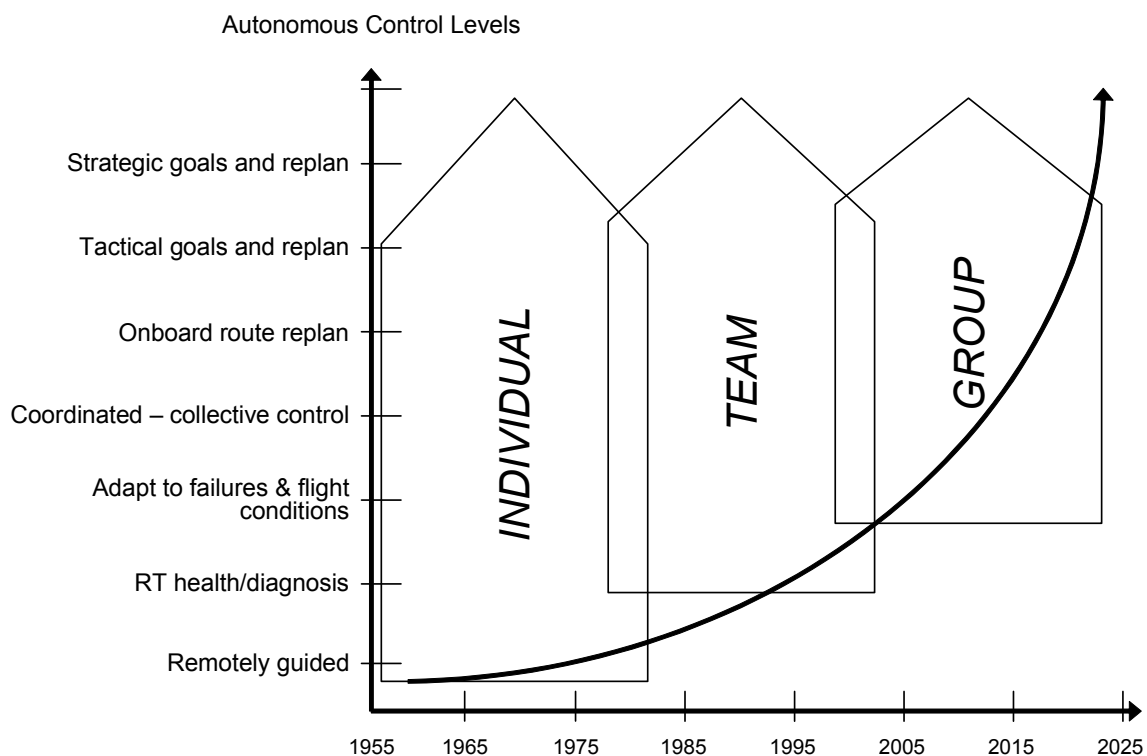


Figure 7-18: Revised ACL Description.

¹⁴ On the other hand, this means that they will appear sequentially with respect to time, rather than as being developed in parallel. That may be a not entirely unwanted side-effect.

¹⁵ All this assumes, of course, that the intentions of the roadmap have been correctly interpreted.

7.7.4 Analysis of UAV Scenarios

The use of the concept of layers of control will be illustrated by describing an UAV scenario. The description will address three characteristic levels of autonomy defined by the 'Roadmap', namely ACL1, ACL6, and ACL9. In terms of the descriptions given above, this corresponds to a remotely guided, single vehicle mission; a group mission; and a team mission.

Table 7-10 shows the scenario that is used. It divides the mission into the three phases of 'ingress', 'over target', and 'egress', where each phase is described further in terms of a number of tasks or functions.

Table 7-10: Overall Description of UAV Scenario

INGRESS	Control, Guidance, Navigation (own ship and attack aircraft)
	Replan
	Communication (C2 MC, attack aircraft, other UAV UCS)
	System management (+contingencies)
	Self defence
	Target location
OVER TARGET	Target registration, identification, verification, designation (for attack aircraft)
	Control, Guidance, Navigation
	System management (+contingencies)
	Communication (C2 MC, attack aircraft, other UAV UCS)
	Sensor management
	Self defence
	Rules of engagement
	Battle damage assessment
EGRESS	Control, Guidance, Navigation
	Communication (C2 MC, attack aircraft, other UAV UCS)
	System management (+contingencies)
	Self defence

One thing to notice about this scenario description is that a number of tasks are common to all three phases. These are: (1) Control, Guidance, Navigation (own ship and attack aircraft); (2) Communication (C2 MC, attack aircraft, other UAV UCS); (3) System management (+contingencies); and (4) Self defence. It is therefore reasonable to describe the scenario in terms of specific and common tasks, cf. Table 7-11. This shows that only the 'ingress' and 'over target' phases comprise specific tasks. It would be possible to analyse the scenario in more detail using a recognised task analysis method, such as hierarchical task analysis

or goals-means task analysis. This would actually be necessary to perform a complete analysis of the command and control demands of the scenario, but it cannot be done on the basis of the available material. Further details, as well as expertise knowledge, would be required. For the present purpose the available material is, however, sufficient to illustrate how the tasks that make up the scenario can be characterised in terms of different control layers, as a basis for anticipating the effects of increased automation (autonomy).

Table 7-11: Common and Specific Tasks in the UAV Scenario

	SPECIFIC TASKS	COMMON TASKS
INGRESS	Replan	Control, Guidance, Navigation (own ship and attack aircraft)
	Target location	Communication (C2 MC, attack aircraft, other UAV UCS)
		System management (+contingencies)
		Self defence
OVER TARGET	Target registration, identification, verification, designation (for attack aircraft)	Control, Guidance, Navigation (own ship and attack aircraft)
	Sensor management	System management (+contingencies)
	Rules of engagement	Communication (C2 MC, attack aircraft, other UAV UCS)
	Battle damage assessment	Self defence
EGRESS		Control, Guidance, Navigation (own ship and attack aircraft)
		Communication (C2 MC, attack aircraft, other UAV UCS)
		System management (+contingencies)
		Self defence

7.7.4.1 Description of Common Tasks

The four common tasks of this scenario are:

- Control, guidance, and navigation (own ship and attack aircraft). This is a composite task, which has at least the three components listed here. We shall further focus on the vehicle itself, since, e.g., guidance of attack aircraft reasonably might be subsumed under communication. In this case ‘control’ is understood as corresponding to tracking, i.e., keeping yaw, pitch, roll, etc., within design and operational limits. As such it is clearly something that is done automatically by the vehicle, as it

is for all modern aircraft.¹⁶ Guidance and navigation involve the layers of monitoring and regulation. The control inputs to the vehicle will typically be in terms of the course, speed, and altitude needed to execute specific manoeuvres or reach specific goals. The goals themselves are both those that are defined by the mission (pre-planned) and those that arise as a result of contingencies, i.e., system management and self defence.

- Communication (C2 MC, attack aircraft, other UAV UCS). This is understood to comprise maintaining contact with the base as well as communicating with other entities involved in the mission (attack aircraft, etc.). It can therefore be seen as part of the monitoring – and to some extent of the regulating – of the mission as a whole, rather than tasks that specifically are part of what the vehicle does. The mission of the vehicle may indeed be seen as serving the purpose of communication, i.e., providing information as a necessary input to a superordinate task, i.e., that of achieving the larger mission objective.
- System management (+contingencies). These are clearly tasks that correspond to the monitoring layer of the ECOM. As mentioned above, monitoring can be of the vehicle itself as well as of the environment. In that later case it may lead to the formation of new goals, cf. below.
- Self defence. In order for the vehicle's mission to be accomplished, it must obviously be able to maintain its functional integrity, which means the ability to defend itself in various ways. The defence can, for instance, be by evasive manoeuvres or by direct counteraction. In relation to the ECOM, self defence can be seen as a targeting activity, i.e., the formation of situation specific goals – which may possibly supersede pre-defined mission goals. Needless to say, targeting is based on processing of incoming information, hence monitoring. A new goal established in this way will give rise to new loops on the monitoring and regulating layers, cf. the description above.

The relations among the ECOM layers and the common mission tasks is summarised in Table 7-12.

Table 7-12: ECOM Characterisation of Common Mission Tasks

Common Mission Tasks	Corresponding ECOM Layer			
	Targeting	Monitoring	Regulating	Tracking
Control, guidance, navigation		X	X	Autonomous
Communication (C2 MC, attack aircraft, other UAV UCS)		X	(X)	
System management (+ contingencies)		X		
Self defence	X	(X)		

7.7.4.2 Description of Specific Tasks

The six specific tasks are found in the 'ingress' and 'over target' phases.

- Ingress: Replan. In the original task description this appears as a subsidiary task to 'control, guidance, navigation'. It is therefore appropriate to see it as associated with targeting, or rather re-targeting.

¹⁶ Similar developments are found in land-based vehicles, even for civilian purposes, and in maritime vehicles.

It takes place in response to an external command, and as a result leads to changes (i.e., new goals) for both monitoring and regulating.

- **Ingress:** Target location. This is a specific, composite activity which best can be interpreted as higher-level regulating. It is composite in the sense that it comprises monitoring of the current position and of the environment, in order to recognise the target. This may in turn require specific manoeuvres (regulating) to bring the vehicle sufficiently close to the target. Target location thus entails both monitoring and regulating.
- **Over target:** Target registration, identification, verification, designation (for attack aircraft). One of the main goals of an UAV is to identify a target and to communicate that information to the mission centre or to, e.g., an attack aircraft. In terms of the ECOM, target registration is mainly a question of monitoring the environment in combination with communication (as a common mission task).
- **Over target:** Sensor management. This is understood as being the management of the various types of information (sensors, channels), to make the best use of the available information for the current goal/action. It can thus be seen as a kind of internal regulating, not of the vehicle's behaviour, but rather the selection and processing of sensor input to be optimally responsive to the needs of the current task. In terms of the ECOM, sensor management is a special kind of regulating.
- **Over target:** Rules of engagement. The rules of engagement (ROE) provide guidance governing the use of force consistent with mission accomplishment [27]. The ROE can therefore be seen as defining part of the performance envelope for the vehicle, specifically the behaviour that under normal circumstances is prohibited. In order to meet the ROE it is therefore necessary to monitor the situation and to abandon specific actions if they are in conflict with the ROE. Seen as a task, 'rules of engagement' therefore entail both monitoring and regulating.
- **Over target:** Battle damage assessment. This is a straightforward case of monitoring for specific changes. It may produce specific manoeuvres as a way of getting the recording the needed data. Battle damage assessment thus comprises monitoring and possibly regulating.

The relations among the ECOM layers and the specific mission tasks is summarised in Table 7-13.

Table 7-13: ECOM Characterisation of Specific Mission Tasks

Specific Mission Tasks	Corresponding ECOM Layer			
	Targeting	Monitoring	Regulating	Tracking
Replan	X			
Target location		X	X	
Target registration, identification, verification, designation (for attack aircraft)		X		
Sensor management			X (internal)	
Rules of engagement		X	X	
Battle damage assessment		X	(X)	

7.7.5 Control, Automation and Views

Designing for control can be viewed in different ways, ranging from graphical interface design to intelligent, autonomous agents or even virtual reality avatars. Within cognitive systems engineering, understanding the nature of control is a prerequisite for the design of the elements of control such as interfaces and information presentation. As mentioned above, the essence of control is that unwanted variability in the process, which may lead to deviations from the desired or prescribed course of development, is reduced to a minimum or does not occur at all. Effective control therefore requires the ability to detect such variability and to respond to it, which in most cases also means the ability to anticipate large fluctuations and prevent them from happening. A system for effective control must therefore support three different types of view: a view of what has happened (the past), a view of what happens here and now (the present), and a view of what may possibly happen (the future).

If the notion of the three different views is applied to the four layers of control, it is evident that not all views are important at each layer. Targeting, for instance, is concerned with developing plans for future actions, while tracking is more about responding to changes in the situation. Indeed, the differences in the type of control (feedback, feedforward) involved at each layer give rise to different demands for data and information. A proposal for the relative importance of the three different views is shown in Table 7-14.

Table 7-14: Relations between Control Layers and Process Views

View	Control Layers			
	Tracking (feedback control)	Regulating (feedforward + feedback control)	Monitoring (feedback control)	Targeting (feedforward control)
Past			Important	Very important
Present	Very important	Very important (Feedback)	Very important	
Future		Very important (Feedforward)		Very important

Getting the information provided by each view involves a cost, most obviously in terms of time. Making use of the information – processing it, understanding it – also takes time, which generally increases with the complexity of the information. Since the process that is controlled usually cannot wait, the management of time is a critical issue in the design of control systems [28,12]. This is certainly the case for the control of a vehicle, not least if it is uninhabited.

7.7.5.1 Control and Time

At the tracking and regulating layers, time is very short – and may in some cases be so short that humans hardly can be involved. A driver can steer a car (tracking layer control) when (s)he is in it, mainly because (s)he is able directly to perceive the environment – at least during daylight. It would be very hard to do this by remote control, since important cues such as motion feedback are missing, even in a full-blown synthetic sensory environment. At the regulating layer human control may be possible depending on the speed of the vehicle (a ship, a land vehicle, a flying drone), although in most cases it is still impractical. At both layers

automation may therefore be necessary to achieve sufficiently fast performance; modern cars, especially at the high-end, are a good example of that. At the monitoring and targeting layers the demands to rapid responses are smaller, but automation may be needed for other reasons, e.g., to achieve steadiness and regularity of functions or to be able to address multiple, simultaneous processes.

While most of the sources of information comprising the different views are external to the controller, for instance sets of local and remote sensors, some information comes from the controlling system itself. The regulating layer needs information about what happens at the tracking layer, the monitoring layer needs information about what happens – and has happened – at the regulating layer, and so on. Even a partial loss of information may lead to a degradation of control and possibly destabilise the dynamic equilibrium among the different layers. Since automation often leads to a loss of information, the principle of layers of control described by the ECOM provides a potentially powerful tool for analysing and understanding how such effects may arise and how they may affect how well the controlling system performs.

7.7.6 Conclusions

A first analysis of the selected UAV scenario shows that it comprises a number of common and specific tasks. The specific tasks can be seen as constituting one line of activity, which serves the primary purpose of the scenario, i.e., a successful mission. The common tasks can be seen as constituting four parallel lines of activity, which must be carried out more or less continuously in order to ensure that the specific tasks can be successfully accomplished. As a result, the scenario presents itself as comprising five parallel lines of activity rather than just one.

7.7.6.1 Effects of Automation on Common and Specific Tasks

The ECOM characterisation of the common and specific tasks provides a basis for considering the feasibility of automation for various mission types. In general, tasks comprising regulating are the easiest to automate from both a technical and a human factors point of view. For an individual mission, this involves the automation of remote guidance in the sense that the execution of actual manoeuvres is done autonomously. This is feasible to the extent that all possible manoeuvres can be anticipated or synthesised. Otherwise it falls prey to the ‘ironies of automation’ [29]. For a team/swarm mission, regulating corresponds to the remote collective control of the swarm, which, as noted above, can be considered as one unit. Given that the automation of a single vehicle is possible, it should therefore also be possible to automate the regulating of a swarm.

The situation is somewhat different for a group, since the individual members of a group need not behave in a uniform manner (cf., the above distinction between a group and a swarm discussed above). This makes the regulating (as automated remote control) of a group more complex since it requires the coordinated regulating of a number of individual vehicles. It may be possible to the extent that the coordination complies with a pre-defined pattern or patterns, but if that is not the case, the coordination will require targeting and monitoring functionality that makes it unsuitable for automation.

Tasks comprising monitoring are in general also well-suited for automation. Regular or routine monitoring has traditionally been one of the earliest functions to succumb to automation, since it is a function that machines perform far better than humans. In terms of the descriptions given above, this applies to all three types of missions. Among the common tasks, monitoring associated to ‘control, guidance, navigation’, ‘system management’ and ‘self defence’ can probably be automated for all types as well. Among the specific tasks, the same goes for ‘target registration’, ‘rules of engagement’, and ‘battle damage assessment’, but probably

not for ‘target location’, as the latter may vary considerably with the context. Again, the problem may be more difficult for a group type of mission, since it involves differentiated roles or functions of individual vehicles.

Tasks comprising targeting can, on the whole, not easily be automated – regardless of mission type. This is a simple consequence of the fact that automation is feasible only for situations or conditions that have a high degree of regularity and predictability. The aspirations and promises of artificial intelligence notwithstanding, the take-over by technology of more complex cognitive functions has generally been unsuccessful on a real-life scale (e.g., [12]). For the proposed scenario, it is only the common task of ‘self defence’ and the specific task of ‘re-planning’ that correspond to the ECOM targeting layer. For ‘self defence’, autonomous functioning may be possible for common threat scenarios, but in that case it may actually be a question of monitoring-induced regulating rather than of targeting as such. For ‘re-planning’, autonomous functioning is probably neither advisable nor feasible, not even within the time span of the Roadmap.

Each of the tasks can be further characterised in terms of the ECOM, with respect to the control layers that are involved. This analysis shows that the monitoring and regulating layers dominate. The targeting layer occurs a few times, while the tracking layer is assumed already to be completely automated. The characterisation of tasks in terms of layers of control provides a basis for assessing the feasibility of automating specific tasks and functions. The general principle is that regulating tasks usually are amenable to automation, while monitoring tasks are so to the extent that they are regular and predictable. Tasks involving targeting are not considered as likely candidates for automation.

In addition to considering each task on its own, it is also necessary to consider the implications of having five parallel lines of activity. In terms of the ECOM, this corresponds to having five parallel control structures. In order fully to appreciate the consequences of proposed automation, it is necessary to analyse the dependencies among the five lines of activity, in terms of interacting goals, inputs, and outputs, in addition to doing so also within each line of activity. An analysis of this type has not been attempted here, but may be carried out following the same principles or – if risk is an issue – the principles of functional resonance [30].

7.7.6.2 The Way Ahead?

In the top-down approach, concerns about the level of automation are secondary to the ability to stay in control. This means that the discussion changes from a comparison of system components and functions to a description of how well the system is able to accomplish its purpose. Noting, for instance, that “the machine suggests one alternative and executes that suggestion if human approves” does not say very much about the nature of control – except that it must take place at a pace so slow that there is time for such consultation. A high level of automation, or even full automation, is not in itself negative or bad. Neither is a low level of automation inherently desirable. It all depends on what the joint system is required to do.

Describing system performance by means of layers of control makes it easier to consider the consequences of automation, hence to make sensible decisions about function allocation. A joint cognitive system is defined by its ability to modify its pattern of behaviour on the basis of past experience to achieve specific anti-entropic ends, and automation may affect this ability in both a positive and negative direction. By starting from an understanding of control as the ability to prevent unexpected conditions from arising and to recover from them, should they occur, the effects of design decisions are easier to see. This goes both for the dynamic equilibrium among the four different layers of control, and the information needed to sustain the views of past, present and future events. The top-down approach forces a view of the system as a whole, and thereby weakens possible implicit assumptions about what men are better at and what machines are better at. Since it is impossible completely to predetermine the environment in which joint systems must function, every effort

should be made to ensure that they have the capabilities needed successfully to achieve their purpose, and to maintain control even when things do not go as planned.

7.7.7 References

- [1] Miller, G.A., Galanter, E. and Pribram, K.H. (1960). Plans and the structure of behavior. New York: Holt, Rinehart & Winston.
- [2] Wiener, N. (1964). God & Golem, Inc. A comment on certain points where cybernetics impinges on religion. The MIT Press, Cambridge, Massachusetts.
- [3] Taylor, F.W. (1911). The principles of scientific management. New York: Harper.
- [4] Fitts, P.M. (Ed). (1951). Human engineering for an effective air navigation and traffic-control system. Ohio State University Research Foundation, Columbus, Ohio.
- [5] Sheridan, T.B. and Verplank, W.L. (1978). Human and computer control of undersea teleoperators. Cambridge, MA: MIT Man-machine system laboratory.
- [6] Sheridan, T.B. (2002). Humans and automation: System design and research issues. New York: John Wiley & Sons, Inc.
- [7] Corcoran, W.R., Portet, N.J., Church, J.F. and Cross, M.T. (1980). The critical safety functions and plant operation. IAEA Conference.
- [8] Newell, A. and Simon, H.A. (1972). Human problem solving. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.
- [9] Lind, M. and Larsen, M.N. (1995). Planning and the intentionality of dynamic environments. In: J.-M. Hoc, P.C. Cacciabue and E. Hollnagel (Eds.), Expertise and technology: Cognition and human-computer interaction. Hillsdale, N. J. Lawrence Erlbaum Associates.
- [10] Hall, A.D. and Fagen, R.E. (1968). Definition of system. In: W. Buckley (Ed.), Modern systems research for the behavioural scientist. Chicago: Aldine Publishing Company.
- [11] Hollnagel, E. and Woods, D.D. (1983). Cognitive systems engineering: New wine in new bottles. International Journal of Man-Machine Studies, 18, 583-600.
- [12] Hollnagel, E. and Woods, D.D. (2005). Joint cognitive systems: Foundations of cognitive systems engineering. Boca Raton, FL: CRC Press/Taylor & Francis.
- [13] Conant, R.C. and Ashby, W.R. (1970). Every good regulator of a system must be a model of that system. International Journal of Systems Science, 1(2), 89-97.
- [14] Hollnagel, E. (1999). Modelling the controller of a process. Trans. Inst. MC, 21(4-5), 163-170.
- [15] Schützenberger, M.P. (1954). A tentative classification of goal-seeking behaviours. Journal of Mental Science, 100, 97-102.

- [16] McRuer, D.T., Allen, R.W., Weir, D.H. and Klein, R.H. (1977). New results in driver steering control. *Human Factors*, 19, 381-397.
- [17] Rasmussen, J. (1986). *Information processing and human-machine interaction: An approach to cognitive engineering*. New York: North-Holland.
- [18] Michon, J.A. (1985). A critical view of driver behavior models. What do we know, What should we do? In: L. Evans and R. Schwing (Eds.), *Human behavior and traffic safety* (pp. 485-525). New York: Plenum press.
- [19] Hollnagel, E. (1993). *Human reliability analysis: Context and control*. London: Academic Press.
- [20] Hollnagel, E., N  bo, A. and Lau, I. (2003). A systemic model for Driver-in-Control. 2nd International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, July 21-24, Park City, Utah.
- [21] Huang, H.-M., Messina, E. and Albus, J. (2003). *Autonomy Level Specification for Intelligent Autonomous Vehicles: Interim Progress Report*. Proceedings of the 2003 Performance Metrics for Intelligent Systems Workshop, National Institute of Standards and Technology (NIST), Gaithersburg, MD, August 16-18.
- [22] DOD (2002). *Unmanned aerial vehicles roadmap 2002-2027*. Washington, DC: Office of the Secretary of Defense.
- [23] Reising, J. (2004). *Synthesizing Perspective – Supervisory Control and Decision Support Concepts*. (From USAF Aircraft: What will the Future Hold? ASC 04-1332 12 May 04).
- [24] Kaber, D.B. and Endsley, M.R. (2004). The effects of level of automation and adaptive automation on human performance, situational awareness and workload in a dynamic control task. In: *Theoretical Issues in Ergonomics Science*, 5(2), 113-153.
- [25] Dekker, S.W.A. and Hollnagel, E. (2004). Human factors and folk models. *Cognition, Technology & Work*, 6, 79-86.
- [26] Clough, B. (2002). UAV's swarming? So what are those swarms, what are the implications, and how do we handle them? Proceedings of AUVSI Unmanned Systems, July 2002. Association for Unmanned Vehicle Systems International, 1-15.
- [27] CJCSI (2000). *Standing rules of engagement for US forces* (CJCSI 3121.01A, 15 January 2000). Washington, DC: Chairman of the Joint Chiefs of Staff Instruction.
- [28] Hollnagel, E. (2002). Time and time again, *Theoretical Issues in Ergonomics Science*, 3, 143-158.
- [29] Bainbridge, L. (1983). Ironies of automation. *Automatica*, 19(6), 775-779.
- [30] Hollnagel, E. (2004). *Barriers and accident prevention*. Aldershot: Ashgate.

7.8 SYNTHESIZING PERSPECTIVE – SUPERVISORY CONTROL AND DECISION SUPPORT CONCEPTS

The U.S. Navy is depending very heavily on the versatile F/A-18 Super Hornet as the mainstay of its carrier fighter/attack force in the foreseeable future. In addition, an electronic attack version is also planned to augment the attack force, with deliveries starting in 2009. Aircraft will have either one or two crewstations depending on the version. On the Air Force side, the F/A-22 Raptor and the F-35 Joint Strike Fighter are the latest aircraft. Both will have a single person in the crewstation. The Navy and Marine Corps also plan to purchase the F-35. The first deliveries of the Air Force and Marine Corps versions of the F-35 will be in 2008, with the Navy's first deliveries starting in 2010. The bottom line is that these three aircraft will provide the two Services' fighter/attack force well into the future [1] – but what type of aircraft will we have beyond these? And what type of crewstation will they have?

One of the issues currently being addressed is the role of future long-range bombers within the Air Force. "The Air Force is rethinking long-range strike, a term that used to mean only one thing: big bombers. As the service adjusts to the Pentagon's new capabilities-based strategy and focuses on desired effects rather than the platforms needed to achieve them, the eventual successor to today's bomber fleet remains intentionally unsettled." [2, p. 29]. The various versions being studied include not only conventional bombers as we think of them, but also various types of space planes. Another interesting aspect of these long-range strike vehicles is whether they will have a crew onboard or on the ground. Among the options being considered are systems with no airborne crew which means it may become an Uninhabited Aerial Vehicle (UAV) [3] (The term "uninhabited" was chosen deliberately; we think it is more accurate than the term "unmanned" which implies only a man would not be aboard these vehicles).

7.8.1 Uninhabited Aerial Vehicles

UAVs have become well-known based on the conflict in Afghanistan. They served to give the command and control authorities continuous pictures of possible targets and also enabled a dramatic reduction in the time from which the target was identified until it could be engaged.

A number of NATO countries are now using UAVs to augment their forces, especially in performing tasks that are dull, dirty, or dangerous. Force augmentation issues relevant to the human operator exist on several levels, including individual UAV control station design, vehicle interoperability by different organizations, and integration of UAVs with manned systems. Human interface issues associated with individual UAV control station design include guaranteeing appropriate situational awareness for the task, minimizing adverse effects of lengthy system time delays, establishing an optimum ratio of operators to vehicles, incorporating flexible levels of autonomy (manual through semi-autonomous to fully automatic) and providing effective information presentation and control strategies. UAV interoperability requires development of a standard set of control station design specifications and procedures to cover the range of potential UAV operators and applications across military services and countries.

Finally, for UAVs to be successful, they must be fully integrated with manned systems so as to enhance the strength of the overall force. Human factors considerations in this area include how manned systems should best collaborate with UAVs, deconfliction concerns, operation with semiautonomous systems, and command and control issues. The essence of this paragraph can be summarized by the following statement: What is the proper role for the operator of UAVs? The operator's role can be defined in terms of three key factors.

7.8.1.1 Factor 1: Advanced UAV Operator Control/Display Interface Technologies

The operators' stations for the U.S. Air Force's Predator and Global Hawk UAVs are mounted in vans with the operators sitting at command and control stations. The ground-based operators of these two vehicles control them quite differently. The Predator, at least in the landing in takeoff phase, uses tele-operation with the operator actually flying the vehicle from a distance. The Global Hawk, on the other hand, takes off and lands automatically and is largely autonomous during its mission. The operator, using supervisory control, "flies" the Global Hawk by using a mouse and keyboard, not stick and throttle. Not all UAV control stations are large enough to be housed in vans, the operator station for the U.S. Marine Corps's Dragon Eye UAV, for example, is the size of a small suitcase which makes it easily transportable (Figure 7-19).



Figure 7-19: Predator Operator Station (left) and Dragon Eye Operator Station (right).

Research efforts with the Predator console have addressed a number of control and display features. Two examples are: head-coupled head-mounted display applications [4] and tactile system alerts [5]. Two additional efforts will be discussed more in detail.

As an example of a display enhancement, Draper, et al. [6] examined four different display formats which would aid the ability Air Vehicle Operator (AVO) and the Sensor Operator (SO) to determine target location. If the AVO located a target in the wide field-of-view camera, it was often difficult to communicate the location to the SO who had a narrow field-of-view camera. Four different formats were examined to improve communication between the two crewmembers (Figure 7-20).

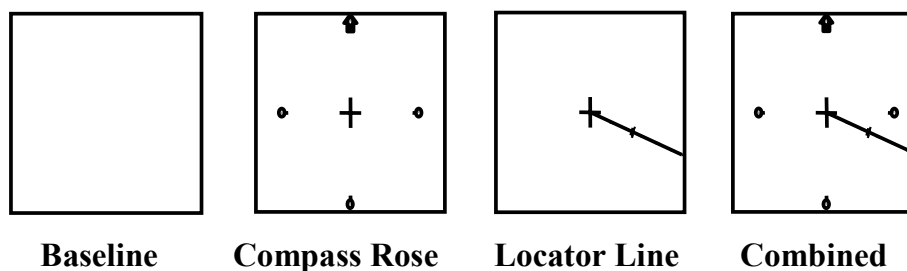


Figure 7-20: Display Concepts.

The results showed that the two formats utilizing the locator line were significantly better than the others. "Time to designate targets was reduced an average of almost 50% using the telestrator [locator line] ..." [6, p. 3-88]. The reason for the superiority of the locator line was that once the AVO designated the target it gave the SO a direct bearing to the target, thereby providing a very efficient means of exchanging information between the two operators.

As an example of control research, Draper et al., [7] compared manual versus speech-based input involving the use of menus to complete data entry tasks. Pilots also performed flight and navigation tasks in addition to the menu tasks. Results showed that speech input was significantly better than manual for all eight different kinds of data entry tasks. The overall reduction was approximately 40% in task time for voice entry when compared with manual input. The operators also rated manual input as more difficult and imposing high workload than the speech method. The reason for the superiority of the voice system was that it enabled the operator to go directly to the proper command without having to manually drill down through a number of menus sublevels in order to find the proper command.

Different types of control modes for operators' consoles were discussed in a recent conference [8]. One recurring theme was a strong desire to move away from tele-operation of the UAVs and progress towards a combination of semiautonomous and fully autonomous operation of these vehicles – regardless of the type of operator console. In order to achieve this goal, a significant amount of automation will be required, especially, when coupled with the desire, in the case of UAVs, to move from a situation where a number of operators control one vehicle to one operator controlling a number of vehicles.

Research exploring the issues of one operator controlling multiple vehicles is just beginning. Barbato, Feitshands, Williams and Hughes, [9] examined a number of operator console features that would aid the operator in controlling four Uninhabited Combat Aerial Vehicles (UCAVs). The mission was to carry out a Suppression of Enemy Air Defences. The operator's console contained three liquid crystal displays onto which was presented a situational awareness (SA) map, UCAV status and multifunction information. The SA format presented the overall geographical situation along with, among other information, the flight routes of the four aircraft. The participants were required to manage the flight routes in two ways: manual versus semiautomatic using a route planner. Although the operators were favorable towards the real-time route planner, they did want information regarding what the real-time planner was actually doing (its intent) and they wanted both the original route and the planned route displayed in order to evaluate the two against each other. In essence, the study showed that a single operator could manage four UCAVs – so long as there were not too many unexpected events.

7.8.1.2 Factor 2: Supervisory Control and Decision Support Concepts

In the case of the UAV, the avionics will be partly contained in the flying platform and partly incorporated into the operator's console, whether airborne or ground based. In either case, because of present day capabilities in computers and intelligent agent software, the resulting product can be much closer to a true team. Operator-machine relationships are being created which emulate those occurring between two human crewmembers – mutual support and assistance. A diagram depicting this overall relationship is shown in Figure 7-21.

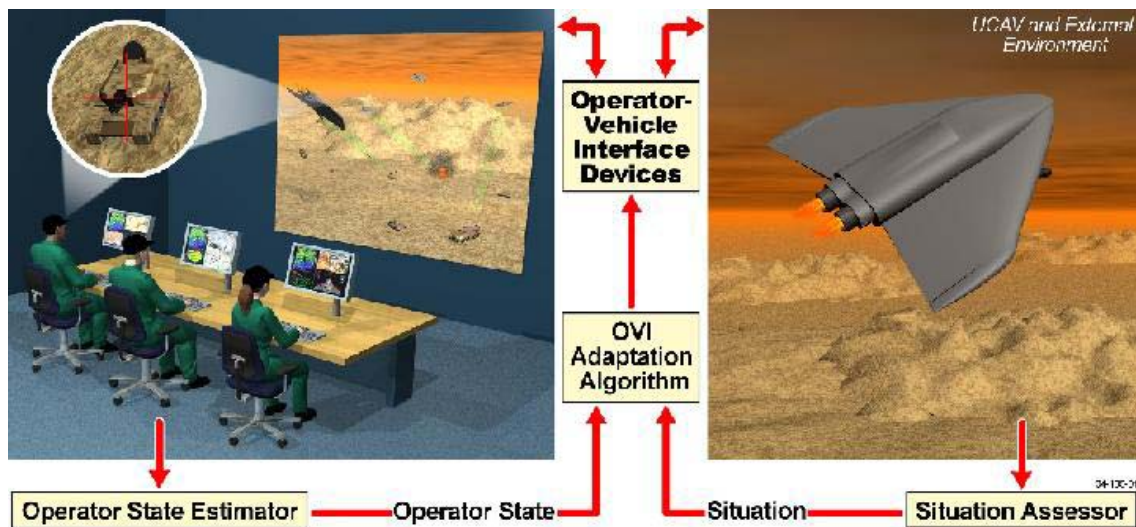


Figure 7-21: Operator-UAV System Diagram.

A major component in achieving this mutual support and assistance is through software entitled associate systems. “Associate systems are computer-based aiding systems that are intended to operate as an associate to the human user” [10, p. 221]. Following from his definition, Geddes goes on to list three very important rules for associate systems and their relationship with the human operator.

- Mixed Initiative – both the human operator and decision aid can take action.
- Bounded Discretion – the human operator is in charge.
- Domain Competency – decision aid has broad competency, but may have less expertise than the human operator.

Because of the mixed initiative aspects of an associate system, function allocation, which assigns roles to the operator and the computer based on their abilities, has to be looked at in an entirely new light. The idea of function allocation has been around since the 1950s and had as its basic premise that the role of operator and the machine (computer), once assigned, would stay relatively constant during the operation of the system. However, this premise does not hold for modern computers since they contain associate systems which can have varying levels of automation at different times during a particular mission; therefore, static function allocation is no longer applicable [11]. Rather, *dynamic* function allocation is a key feature of associate systems with varying levels of automation.

Taylor [12], illustrates how dynamic function allocation changes the working relationship between the Human Operator and the Machine (with associate system based automation); this changing relationship is shown in Figure 7-22.

Co-operative Functionings

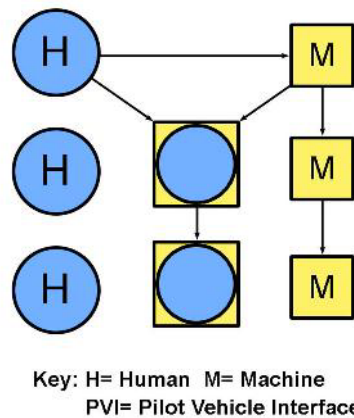


Figure 7-22: Systems Authority Concepts – H = Human; M = Machine (from [12, p. 2-17].

Co-operative Functionings indicates how the operator (H in the figure) and automation (M in the figure) would work together in an associate system. It is quite different from both manual control and supervisory control. In manual control, the human operator specifies the goals and functions to be accomplished and the machine carries out the tasks. In the next level, supervisory control, the human operator still specifies the goals, but the machine carries out both the tasks and functions. In the co-operative functionings (associate system), the human operator and machine interact at all levels, and *either* can perform the goals, functions and tasks. It is through this dynamic sharing of authority that the operator and the associative can begin to operate as a team – an operator and a type of electronic crewmember (EC). However, to function as a team, the operator must trust the EC.

7.8.1.3 Factor 3: Trust and Levels of Automation

One means of establishing operator trust in the EC is to allow the operator to decide how much authority or autonomy, called levels of automation (LOA), to give the EC. “LOA defines a small set (‘levels’) of system configurations, each configuration specifying the degree of automation or autonomy (an ‘operational relationship’) at which each particular subfunction performs. The pilot sets or resets the LOA to a particular level as a consequence of mission planning, anticipated contingencies, or inflight needs” [13, p. 124]. While originally conceived for a piloted aircraft, LOAs apply equally well to UAV consoles and their operators. One question that must be answered is how many levels of automation should be assigned to the associate? A number of researchers have examined this issue. The result is as many as 10 [14] and as few as 5 [15].

In order to create an effective team, once the levels are determined, the next task is to determine how they relate to the way humans process information. A further expansion of LOA was proposed by Parasuraman, Sheridan and Wickens [16]; they matched levels of automation with a four stage human information processing model (information acquisition, information analysis, decisions selection, and action implementation). The 10 LOAs are based on a model proposed by Sheridan [14]. They then illustrate how various systems could have different levels of automation across the four portions of the information processing model. This work is very important because it begins to blend levels of automation with human information processing capabilities. The authors realize that the model is not finalized, “We do not claim that our model offers comprehensive design principles but a simple guide.” (p. 294) However, it certainly is in the

right direction towards achieving an optimal matching between automation and human capabilities for particular systems.

Using automation levels and having an indication of the information processing workloads of the mission, the operators could establish a “contract” with the EC in the pre-mission phase. They could, through a dialogue at a computer workstation, define what autonomy they wish the EC to have as a function of flight phase and system function. As an example, weapon consent would always remain exclusively the operator’s task, but reconfiguration of the UAVs flight control surfaces to get the best flight performance in the event of battle damage would be the exclusive task of the EC.

7.8.2 Adaptive Automation

Although the pre-mission contract with the EC helps to establish roles for it and the human operator, the functions allocated to each crewmember remain static throughout the mission. However, missions are highly dynamic, and, as stated before, it would be desirable to change the function allocation during the mission. This dynamic function allocation is achieved through adaptive automation. “In adaptive automation, the level or mode of automation or the number of systems that are automated can be modified in real-time. Furthermore, both the human and the machine share control over changes and the state of automation” [17, p. 43].

Two of the key aspects of adaptive automation are *when* to trigger the shift and for *how long*. The *when* aspect is discussed by Scerbo, Parasuraman, DiNocera and Prinzl [18, p. 11] who list a number of methods for triggering the shifting tasks between the operator and the automation: critical events, operator modeling, performance measurement, psychophysiological measurement and hybrid methods. A diagram of how many of these allocation methods can be used in a system is shown in Figure 7-23.

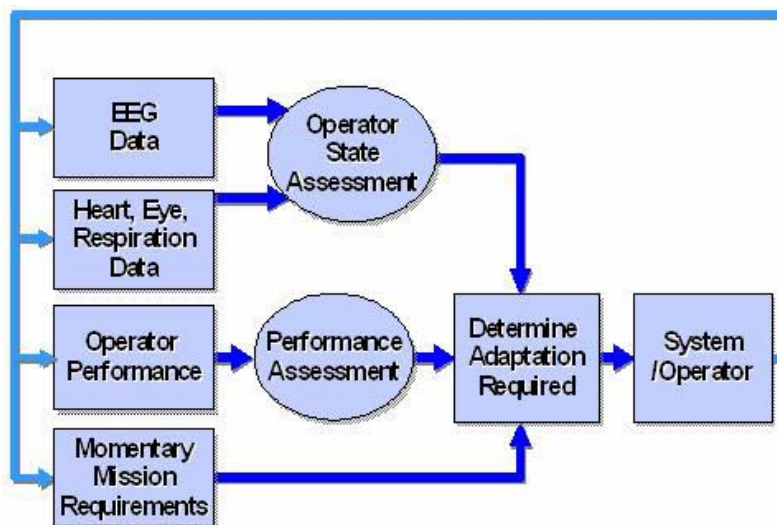


Figure 7-23: Adaptive Automation System Diagram.

As an example of how psychophysiological measurement is used to determine operator state Wilson and Russell [19] required U.S. Air Force air traffic controllers, in a simulation, to manage air traffic around the Los Angeles airport. The task loading was manipulated by the number of aircraft they had to manage

(volume) and the different kinds of aircraft they had to manage (complexity). The tasks were first given to subject matter experts, and the difficulty was increased until they verified that they were in an overload condition and could not effectively handle the traffic. The participants were then given the same type of task and their physiological data was processed by an artificial neural net. The result was the neural net could identify the non-overload condition 99% of the time and the overload condition 96% of the time. These results indicate that psychophysiological measures may be potentially very useful in determining if the operator is overloaded in real-world applications.

Once the state of the operator can be reliably assessed, the next question is, Can the workload be shifted quickly between the operator and the automation? Wilson, Lambert and Russell [20] addressed this question in a study using NASA's Multi Attribute Test Battery (MATB). There are four tasks in the MATB: tracking, systems monitoring, resource management, and communications. As in the air traffic control study previously discussed, pretest conditions were conducted to discover when the operators were overloaded, and the neural nets were used to identify this condition. In one experimental condition, the participants managed all four of the tasks, regardless of difficulty. In the other condition, when the participants reached the overload condition, the systems monitoring and communications tasks were handed off to the automation. The operator continued controlling the tracking and resource management tasks. The results showed that, relative to the manual condition, the adaptive aiding condition resulted in a 44% reduction in tracking error and a 33% error reduction in the resource management task.

The psychophysiological triggering of adaptation appears to be very promising; however, researchers are still very early in applying this technology to real-world settings. "At present, however, there is not enough existing psychophysiological research to provide adequate information on which to base adaptive allocation decisions" Prinzel, Freeman, Scerbo and Mikulka, [21, p. 407]. Although the shifting of tasks from the operator to the automation by psychophysiological methods (the *when* aspect) resulted in successful performance in Wilson et al. [20] study, there doesn't appear to be any general consensus as to *how long* the automation should keep the transferred task in order to optimize overall systems performance. The *how long* aspect has been examined by a number of authors, and the answer appears to be task specific. For example, Scallen and Hancock [22] utilized adaptive automation in a study which required pilots to perform tracking, monitoring, and targeting tasks while flying a simulator. After a target was presented, the tracking task was automated for a 20 second interval, after which it was returned to the pilot. Conversely, in another research effort [23] which looked at three different cycle times between the operator and the automation (15, 30, or 60 seconds), the 15 second switching time resulted in the best tracking performance. However, three of the five pilots who took part in the study reported that the switching back and forth was distracting. As a result, the author states that, "In the case of adaptive allocation systems we propose a moratorium strategy in which there is a minimum frequency with which the system can either assume or relinquish task control." (p. 402)

7.8.3 Putting It Together

Things are getting complicated. We now have levels of automation, human information processing models, and adaptive automation. How do we make sense of all this? Kaber, Prinzel, Wright, and Claman [24] addressed two of the three components in a study which looked at the issue of adaptive automation (AA) relative to the four stages of the information processing model. Besides a manual control condition where there was no AA, it was applied to the all the stages of the four stage model: information acquisition, information analysis, decision making, and action implementation.

The participants used Multitask which created a simulated Air Traffic Control environment. Their task was to provide a landing clearance to various aircraft depicted on the radar scope. The aircraft were flying from the

periphery to the center of the display. An error occurred if the aircraft reached the center of the display, or collided with another aircraft, before the clearance was issued. A gauge monitoring secondary task was also used. If the participant's performance on the secondary task fell below a predetermined level, the primary task would be automated. NASA's Task Load Index (TLX) was used to measure workload.

Although performance utilizing AA was superior to the manual control condition, the results showed that AA was most effective when applied to the information acquisition and action implementation information processing stages. It was not effective in the information analysis and decision making stages. The authors conclude, "All these results suggest that humans are better able to adapt to AA when applied to lower-level sensory and psychomotor functions, such as information acquisition and action implementation, as compared to AA applied to cognitive (analysis and decision making) tasks" [24, p. 23].

The Kaber et al., [24] study began to give some insight into the interaction of two components: information processing and adaptive automation – but as mentioned at the beginning of this section, there are three components, the third being levels of automation. How do they *all* fit together? Kaber and Endsley [25] attempted to show the relationship among all three factors. They constructed 10 levels of automation and an information processing model similar to Parasuraman et al., [16], with the stages being monitoring, generating, selecting, and implementing. In addition, they also incorporated adaptive automation.

They then conducted a study utilizing six levels of automation: manual, action support, batch processing, decision support, supervisory control, and full automation (numbers 1, 2, 3, 5, 9, and 10 in Figure 7-24). Manual and Full Automation are self-explanatory. Action Support is similar to tele-operation. Batch Processing requires the human to create and decide the options to implement and the computer carries these out. Decision Support involves the computer's suggesting options and once the operator selects one of these options (or one self generated), it is then put into operation by the computer. In Supervisory Control the computer generates and carries out the options. The operator monitors and gets involved if necessary. These six levels were then combined with three levels of adaptive automation cycle time (AACT) (20%, 40% and 60%).

LEVEL OF AUTOMATION	ROLES			
	MONITORING	GENERATING	SELECTING	IMPLEMENTING
1. Manual Control	Human	Human	Human	Human
2. Action Support	Human/Computer	Human	Human	Human/Computer
3. Batch Processing	Human/Computer	Human	Human	Computer
4. Shared Control	Human/Computer	Human/Computer	Human	Human/Computer
5. Decision Support	Human/Computer	Human/Computer	Human	Computer
6. Blended Decision Making	Human/Computer	Human/Computer	Human/Computer	Computer
7. Rigid System	Human/Computer	Computer	Human	Computer
8. Automated Decision Making	Human/Computer	Human/Computer	Computer	Computer
9. Supervisory Control	Human/Computer	Computer	Computer	Computer
10. Full Automation	Computer	Computer	Computer	Computer

Figure 7-24: LOA Taxonomy for Human-Computer Performance in Dynamic, Multi-Task Scenarios [25, p. 119].

For example, in a 20 minute trial the task would be allocated to the automation either 4, 8 or 12 minutes. The results showed that, "The best combination of LOA and AACT involved human strategizing combined with computer implementation (Batch processing (LOA 3)) during high automation cycle times (12 min on

cycle and 8-min off cycle)” [25, p. 147]. This result is a big step forward, but also illustrates the difficulty in implementing adaptive automation, levels of automation, and human information processing. If we put this research on a time scale relative to the over 80 years of research in the design of aircraft crewstations, we are just beginning to explore this area. So, we cannot expect instant answers to these very difficult questions. To make matters even more interesting, there are also plans to place varying levels of automation within the airborne platform.

7.8.4 Levels of Automation Within the Air Vehicle

Earlier in this section it was mentioned that there would be intelligent software both in the operator’s console as well as within the UAV itself. The airborne computing system enables varying levels of autonomy called autonomous control levels (ACLs) within the UAV. Ten different levels are shown in Figure 7-25. At first glance, it would seem logical to assume that these 10 levels map onto Sheridan’s 10 levels of autonomy mentioned in Factor 3: Trust and Levels of Automation. Sheridan’s levels deal with the interaction *between* the operator and the UAV. However, these ACLs are referring to autonomy levels *within* the aircraft only and not between the aircraft and the operator. One of the interesting things about this chart is that the lower levels of the chart refer to the ACLs within *each* aircraft in, for example, a flight of four – but from levels five and higher, they referred to how the *entire flight* works together as a group. The ten levels of autonomy in Figure 7-25 range from Level 1: Remotely Guided (tele-operation) to Level 10: Fully Autonomous Swarms where the vehicles are acting in concert with one another to achieve a common goal.

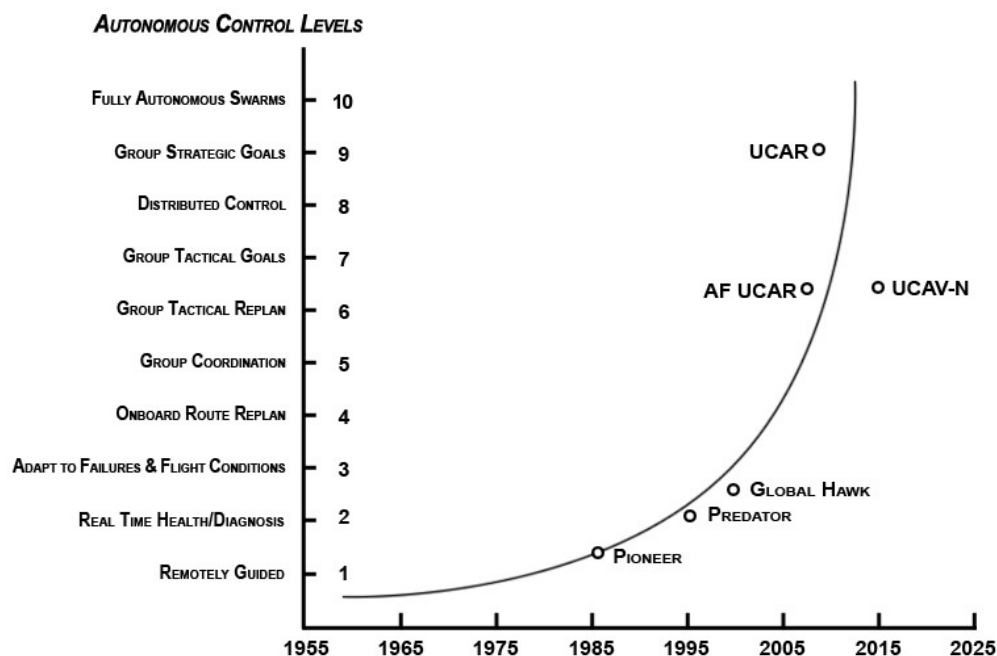


Figure 7-25: Aircraft Control Levels [from 26, p. 84].

Tele-operation has already been discussed in Factor 1: Advanced UAV Operator Control/Display Interface Technologies and will not be further enumerated upon here – but Level 10: Swarms, which offer a whole new level of control both within a group of aircraft and between that group and the operator, will be examined in more detail. The interesting thing about swarms is that there doesn’t appear to be any central controller telling

the swarm what to do. If you observe a school (swarm) of fish, they just appear to act as one with no central leader fish giving them directions. The same is true for flocks of birds, groups of ants, and swarms of bees. “ ‘Swarming’ itself is a type of emergent behavior, a behavior that isn’t explicitly programmed, but results as a natural interaction of multiple entities” [27, p. 1]. As an example of forming a swarm, consider how ants communicate that they have found a source of food. What happens is that the ants lay down a pheromone trail (chemical markers) that other ants can follow. The strength of the pheromones, however, decays over time; therefore, the ant that finds the closest food supply and returns with it will have the strongest pheromone trail. Other ants will then follow this trail with no central commander ant directing them to do this [28].

So, what does this have to do with UAVs? If a flight of UAVs could act as a swarm, instead of giving them explicit, detailed instructions on the location of surface-to-air missile batteries, for example, they could be directed to just loiter about a certain area of enemy territory and if they come across the missiles they could destroy them. Of course, they would be acting within the level of responsibility given to them by the human operator. Creating digital pheromones for UAVs is one way they could communicate. These types of pheromones are not based on chemicals, but rather on the strength of electrical fields. In a computer-based (constructive) simulation, a UAV swarm using digital pheromones significantly outperformed the non-swarm case [29].

7.8.5 Conclusion

UAVs have a wide range of avionics sophistication, from the relatively basic Dragon Eye to very complex Global Hawks and UCAVs. Many of the UAVs used at the small unit level will have limited automation although, for example, they will be able to plan their own flight route. However, most future aircraft, whether inhabited or not, will contain associate systems that will incorporate varying levels of autonomy and adaptive automation as basic operating principles. These principles will enable the UAV operator and the associate to form a team consisting of two crewmembers – one human and one electronic. In order to function effectively, the operator and the EC must work together as a close-knit team, and the EC may not only supervise one aircraft, but the entire swarm. One essential feature of a successful team is trust in the other partner. As an example, guidelines to create such trust must include specifying the EC’s level of autonomy. By using these guidelines, a high-quality, trusting relationship can be achieved between the operator and the EC. This internal trust will, in turn, lead to an efficient and effective team which can operate successfully in a system of systems environment.

7.8.6 References

- [1] Schweitzer, R. (2003). Big Bucks for the Best There Is, *Armed Forces Journal*, June pp. 24-28.
- [2] Tirpak, J. (2002). Long Arm of the Air Force, *Air Force Magazine*, October, 28-34.
- [3] Hebert, A. (2003). The Long reach of heavy Bombers, *Air Force Magazine*, November, pp. 24-29.
- [4] Draper, M.H., Ruff, H.A., Fontejon, J.V. and Napier, S. (2002). The effects of head-coupled control and head-mounted displays (HMDs) on large-area search tasks. *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting*, 2139-2143.
- [5] Calhoun, G.L., Draper, M.H., Ruff, H.A., Fontejon, J.V. and Guilfoos, B. (2003). Evaluation of tactile alerts for control station operation. *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting*, 2118-2122.

- [6] Draper, M., Geiselman, E., Lu, L., Roe, M. and Haas, M. (2000). Display concepts supporting crew communication of target location in unmanned air vehicles. Proceedings of the Human Factors and Ergonomics Society 44th Annual Meeting, 385-388.
- [7] Draper, M., Calhoun, G., Ruff, H., Williamson, D. and Barry, T. (2003). Manual versus Speech Input for Unmanned Aerial Vehicle Control Station Operations. Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting. Denver, CO: HFES.
- [8] Association of Unmanned Vehicle Systems International: Unmanned Systems in a New Era, AUVSI Second Annual Ground, Sea and Air Conference (2002), February 12-14, Washington, DC.
- [9] Barbato, G., Feitshands, G., Williams, R. and Hughes, T. (2003). Operator Vehicle Interface Laboratory: Unmanned Combat Air Vehicle Controls and Displays for Suppression of Enemy Air Defences, In: Proceedings of the 12th International Symposium on Aviation Psychology, Dayton, Ohio.
- [10] Geddes, N. (1997). Associate systems: a framework for human-machine cooperation. In: Smith, M., Salvendy, G. and Koubek, R. (Eds.) Designing of Computing Systems: Social and Ergonomic Considerations. Amsterdam: Elsevier.
- [11] Hancock, P.A. and Scallen, S.F. (1996). The future of function allocation. Ergonomics In: Design, Q4, 24-29.
- [12] Taylor, R. (1993). Human factors of mission planning systems: Theory and concepts. AGARD LS-192 New Advances in Mission Planning and Rehearsal Systems, 2-1 – 2-22.
- [13] Krobusek, R.D., Boys, R.M. and Palko, K.D. (1988). Levels of autonomy in a tactical electronic crewmember. Proceedings of The Human – Electronic Crew: Can They Work Together?, 124-132 (Tech. Rep. WRDC-TR-89-7008). Wright-Patterson Air Force Base, OH: Cockpit Integration Directorate.
- [14] Sheridan, T.B. (1980). Computer control and human alienation. Technology Review, October, 61-73.
- [15] Endsley, M.R. (1996). Automation and situational awareness. In: R. Parasuraman and M. Mouloua (Eds.), Automation and human performance: Theory and applications (pp. 163-181). Mahwah, NJ: Erlbaum.
- [16] Parasuraman, R., Sheridan, T.B. and Wickens, C.D. (2000). A model for types and levels of human interaction with automation, IEEE Transactions on Systems, Man, and Cybernetics – Part a: Systems and Humans, Volume 30, No. 3, May, 286-297.
- [17] Scerbo, M.W. (1996). Theoretical Perspectives on Adaptive Automation. In: Parasuraman, R. and Mouloua, M. (Eds.) Automation and Human Performance, 37-63.
- [18] Scerbo, M.W., Parasuraman, R., DiNocera, F. and Prinzel, L.J. (2001). The Efficacy of Physiological Measures for Implementing Adaptive Technology, NASA/TP-2001-211018, p. 11.
- [19] Wilson, G.F. and Russell, C.A. (2003). Operator Functional State Classification Using Multiple Psychophysiological Features of an Air Traffic Control Task, Human Factors, Fall 45 (3), 381-389.

- [20] Wilson, G.F., Lambert, J.D. and Russell, C.A. (2000). Performance Enhancement with Real-time Physiologically Controlled Adaptive Aiding, In: Proceedings of the IEA 2000/HFES 2000 Congress, Human Factors and Ergonomics Society, Santa Monica, California, 3-61 – 3-64.
- [21] Prinzel, L.J., Freeman, F.G., Scerbo, M.W. and Mikulka, P.J. (2000). A Closed-loop System for Examining Psychophysiological Measures for Adaptive Task Allocation. *The International Journal of Aviation Psychology*, 10 (4), 393-410.
- [22] Scallen, S.F. and Hancock, P.A. (2001). Implementing Adaptive Function Allocation, *The International Journal of Aviation Psychology*, 11 (2), 197-221.
- [23] Scallen, S.F., Hancock, P.A. and Duley, J.A. (1995). Pilot Performance and Preference for Short Cycles of Automation in Adaptive Function Allocation. *Applied Economics* Vol. 26, Number 6, 397-403.
- [24] Kaber, D.B., Prinzel, L.J., Wright, M.C. and Claman, M.P. (2002). Workload-Matched Adaptive Automation Support of Air Traffic-control or Information Processing Stages, NASA/TP-2002-211932, September 2002.
- [25] Kaber, D.B. and Endsley, M.R. (2004). The effects of level of automation and adaptive automation on human performance, situational awareness and workload in a dynamic control task. In: *Theoretical Issues in Ergonomics Science*. Taylor & Francis Volume 5, Number 2 / March-April, pp. 113-153.
- [26] OSD UAV roadmap, 2002-2007, December 2002, p. 84, http://www.acq.osd.mil/usd/uav_roadmap.pdf
- [27] Clough, B. (2002). UAV's Swarming? So what are those swarms, what are the implications, and how do we handle them? AUVSI Unmanned Systems 2002 proceedings. Association for Unmanned Vehicle Systems International. July 2002, pp. 1-15.
- [28] Bonabeau, E. and Theraulaz, G. (2000). Swarm Smarts. *Scientific American*, March 2000, pp. 72-79.
- [29] Parunak, H., Purcell, M. and O'Connell, R. (2002). Digital Pheromones for Autonomous Coordination of Swarming UAVs. American Institute of Aeronautics and Astronautics, AIAA 2000-3446, pp. 1-9.

Chapter 8 – CONCLUSIONS AND SUMMARY

Chapter Lead: J. Reising

Contributors: J Reising, R. Taylor

Force augmentation issues relevant to the human operator have been shown to exist on several levels, including individual UMV control station design, vehicle interoperability, and integration of UMVs with manned systems. On the basis of the material reviewed by the RTO HFM-078 Technical Team, and reported in detail in the preceding chapters, many topics, issues and conclusions related to UMV human factors have been raised. In an attempt to summarize this vast effort, five major issues were extracted that cut across several sections of this report. Each issue is followed by a representative sample of conclusions associated with it. These identified conclusions are not at all intended to be exhaustive. Rather they serve primarily to illustrate the general findings and understanding with regards to each issue.

8.1 ISSUE 1: HUMAN AUTHORITY AND RESPONSIBILITY IN DEALING WITH UMVs

In modern asymmetric warfare, well-organized belligerents ignore the legal requirement under international law to be readily distinguished from the civilian population. They merge with the civilian population, they do not travel in identifiable military vehicles and they use sophisticated deception tactics. Thus, in modern warfare, it is very difficult for an autonomous machine to discriminate between civilians and military targets.

8.1.1 Conclusion 1

Experienced human perception and judgment are needed to assess risks, to consider both the immediate and broader context, to judge the consequences and implications of action, and if possible, to anticipate, see through and counter any new deception tactics. Consequently, any autonomous system will remain dependent upon ‘human-in-the-loop’ targeting decisions, where a human makes the ultimate decision to engage a target.

8.1.2 Conclusion 2

Human involvement is required in military operations to direct and plan the use of military capability, and to ensure lawfully correct use of lethal force. This is achieved through the application of human command authority, responsibility and accountability, and competency. With autonomous UMVs, some of that responsibility is delegated to increasingly competent computer controlled machines, but the authority and accountability for the delegation ultimately remains with humans.

8.1.3 Conclusion 3

Methods for expressing detailed system automation level requirements (e.g., Pilot Authorisation and Control of Tasks (PACT)) maintain operators’ authority by enabling them to delegate responsibility for tasks to the computer through a set of contracts that limit autonomy and bound the behavior of the aiding system, while maintaining the operators’ authority through executive control.

CONCLUSIONS AND SUMMARY

8.1.4 Conclusion 4

Delegation approaches to interaction with intelligent yet subordinate human operators have worked repeatedly throughout history and, particularly, the history of warfare. Automation in the form of UMVs will increasingly take its place as one of those actors. Since we want it to be intelligent, capable and effective, yet remain subordinate, we will increasingly need methods for enabling it to interact with us in the ways that we trust and are familiar with. Since delegation is the primary method that fits that bill, it only makes sense to pursue delegation approaches to human interaction with automation.

8.2 ISSUE 2: THE ROLE OF HUMAN OPERATORS WITH ADVANCED AUTOMATED AND INTELLIGENT UMV SYSTEMS

A number of fundamental questions and key issues can be identified concerning the role of humans in advanced automated and intelligent systems. There is an inexorable trade off between higher levels of automation and unpredictability. In particular, there is uncertainty over how to optimize the use of human and computer decision resources, while preserving a human-centric system.

8.2.1 Conclusion 1

Automation must be designed to augment, not hinder, human capabilities. It is critical for appropriate use of automation that the user understand how the automation works and what mode the automation is in. Additionally, operator interfaces must provide rapid visibility into the current status and future plans of automation for shared human-automation situational awareness.

8.2.2 Conclusion 2

Intelligent decision support interfaces will need to be designed such as to allow independent operator assessment of the situation as well as the rationale for any automated classifications/recommendations.

8.2.3 Conclusion 3

The system should perform automatic activities as if they were completed by the operators themselves during automatic task execution. There will be less unattended actions of the system, which improves the operators' awareness and comfort, increasing total system safety and performance. Natural operation is particularly important when the operators have to override the automatic system by switching back to manual control.

8.2.4 Conclusion 4

Automation does not reduce operator workload per se; it may change the nature of the workload or may even increase it. The operators, as supervisors of automated systems, essentially become long-term monitors with periodic requirements to intervene when necessary. The cognitive workload associated with this supervisory control may well be higher than the workload of physical control.

8.2.5 Conclusion 5

All automation is not created equal. It can be brittle, unpredictable, and prone to bias. Knowing about these pitfalls is half the battle. A designer must carefully look at where and how the automation may fail and ensure the operators know the mission impact (if any) of the failure.

8.2.6 Conclusion 6

Human knowledge, experience and judgment provide unique capability to analyze safety risks and to think ahead in uncertain and novel situations. The challenge is to provide information and decision systems that protect and preserve the human operators' key role, and that augment and enhance the operators' cognition rather than replace the operators in complex decision making.

8.2.7 Conclusion 7

New approaches to the use of automation propose adjustable levels of computer autonomy with a strong socio-technical and cognition basis. These seem likely to provide sensible architectures for distributed, multi-agent intelligent systems that can be more readily appreciated by human operators than traditional automation approaches.

8.2.8 Conclusion 8

Automation has often been approached from the bottom up, starting with the system components. An alternative is to approach the problem from the top down, using the requirements to joint system performance as a starting point. In this approach the emphasis is on operators being in control. A multi-layered Extended Control Model (ECOM) provides a good basis for understanding the consequences of automation and the needs of various types of information to support views of the past, present, and future.

8.3 ISSUE 3: INTEROPERABILITY OF UMV SYSTEMS

Migration of operator control is currently regarded as one of the most complex and risky phases of UMV operations. Because it includes changes in the locus of control within functional, temporal, or physical domains, many system parameters may be changed and difficult procedural and technical issues can be involved. For instance, in current long endurance UAV operations, control may be transferred between operators in a control station (e.g., crew changeover), between control stations (e.g., vehicle handoff), or among members of a crew (e.g., task execution). Migrating control between dissimilar systems is particularly difficult because of issues of system synchronization.

8.3.1 Conclusion 1

The control system will need to be designed to allow for system synchronization and facilitate operators' achieving an adequate level of situational and system's awareness so a handover can be safely performed.

8.3.2 Conclusion 2

UAV interoperability requires development of a standard set of control station design specifications and procedures to cover the range of potential UAV operators and applications across military services and countries.

8.3.3 Conclusion 3

Resolving issues associated with connectivity, knowledge and action consistency, and transfer of control must be addressed during the early stages of systems engineering to ensure proper human-centered development of UMV systems within a system-of-systems architecture.

CONCLUSIONS AND SUMMARY

8.3.4 Conclusion 4

Migration of control between operators at physically dispersed locations may require initiation and alignment of systems, one or more data and communications links, and possibly even cryptological equipment. It may also require coordination with external command and control agencies. This situation may be made more complex if a face-to-face debrief is not possible.

8.3.5 Conclusion 5

Migration of operator control needs to be coordinated prior to the actual event. This means the specific procedures and information to be exchanged should be identified during the mission planning process. The procedures should be available in checklist form and should have been previously validated to minimize the unintended effects of operator input errors as well as be applicable to both nominal and off-nominal situations.

8.3.6 Conclusion 6

Since migration of operator control of UUVs demands a high level of crew coordination, all involved personnel should have initial and recurrent proficiency training in control transfer procedures as well as crew coordination.

8.3.7 Conclusion 7

Team performance directly correlates with team members' levels of situational awareness (SA). Accordingly, in order to safely migrate operator control, it is imperative the operators gaining control have at least the same level of SA as the operators releasing control. Operators should strive for the highest level of SA (e.g., level 3 SA) prior to assuming control of a UUV. Level 3 SA is defined as prediction of the future status of one's own situation and the surrounding elements. SA may need to be achieved at the system, operational, and mission levels.

8.4 ISSUE 4: CONTROL STATION DESIGN

There is a vast expanse of data that is available to UUV operators in a network centric environment. Coupled with the limitations of human information processing, autonomous UUV supervisory control issues, and the impact of environmental stressors on cognitive performance, control station designers face a huge challenge to provide a user centered design.

8.4.1 Conclusion 1

It is important that any UUV operator interface design follow a multi-disciplinary user-centered design process. The goal of user-centered design is to ensure the final design meets the users' needs and expectations. The process of requirements definition (user profiles, work flow, task analysis, and information architecture) and repeated interface design development and iteration (through multiple usability assessments and formal evaluations) will increase the likelihood of obtaining fully functional and easy-to-use interfaces.

8.4.2 Conclusion 2

It is important to recognize the unique challenges levied upon the UUV operators including the effects of system time delays, bandwidth limitations (which can be intermittent), datalink degradations/dropouts, and the

loss of multi-sensory information often afforded to onboard operators. However, the physical separation of crew from vehicle might also offer some unique benefits that should be exploited. Besides the obvious benefit to crew safety, it is quite likely that available bandwidth and the variety of available information sources might be, in certain cases, far greater for a geographically-separated UMV crew than for onboard operators, potentially resulting in more situational awareness rather than less.

8.4.3 Conclusion 3

As technology advances, the role of the UMV operators must change as well. Therefore, UMV operator interfaces must be tailored to match the capabilities and limitations of the host system and intended mission. These operator interfaces must take into account issues associated with automation management, including vigilance effects, brittle/clumsy automation, sudden workload spikes, etc.

8.4.4 Conclusion 4

In the future, a new interface paradigm for controlling next generation UMVs may be required to enable a single supervisor to control multiple semi-autonomous UMVs. Because these UMVs will have the capability to make certain higher-order decisions, independent of operator input and pre-defined mission plans, operators will face a new set of challenges. Specifically, they will be required to rapidly judge the appropriateness of these decisions and assess their impact on overall mission objectives, priorities, etc. Future operator interfaces will need to be tailored for multi-UMV control and to allow the operator the capability to easily inspect/override the autonomous UMV decision-making logic. These interfaces will also need to provide information fusing/filtering algorithms, intelligent prioritization/cueing logic, and possibly some form of adaptive task allocation in response to rapidly changing events and/or workload levels.

8.4.5 Conclusion 5

The 'T' arrangement of the airspeed, altitude and heading in aircraft cockpits has led to a standard arrangement in manned aircraft. This has allowed pilots to move from one aircraft to another with minimum levels of negative transfer. No such standards exist for UMV control station design. This has led to vastly different designs by each manufacturer and the result that operators must be trained very specifically on each platform control station, with little or no advantage of previous learning. This lack of standard design components, at least for fundamental information, must be addressed for UMVs to reduce training costs, logistics and operation errors.

8.4.6 Conclusion 6

UMV operator interfaces need to be designed with an understanding of where the human information processing bottlenecks occur in a task flow. As a result, the operator must be given information in a form that is easily perceived, interpreted, and responded to.

8.4.7 Conclusion 7

Since UMV operators are currently limited to a reduced stream of sensory feedback delivered almost exclusively through the visual channel, there is reason to believe that situational awareness and performance may be improved through multi-sensory interfaces. These improvements might stem from an increase in the operators' sense of presence in the remote environment, from increased information throughput provided by multi-sensory stimulation, and/or a more intuitive presentation/control of information. The result can be

CONCLUSIONS AND SUMMARY

improved performance over conventional visual interfaces. Technologies such as spatialized audio, haptic/tactile stimulation and speech recognition systems appear especially relevant to multi-UMV operations.

8.4.8 Conclusion 8

The sense of presence (i.e., “being there”) is often concomitant with engagement on the part of the operators, and this may be critical when the operators take on a supervisory role over semi-autonomous UMVs. In this situation, there exists the potential that the operators will ‘fall out’ of the control loop and may have difficulty re-entering when necessary. Immersion in a virtual environment (i.e., the UMV operator interface) may facilitate intuitive interaction and ensure that the operators remain engaged in the mission even if not directly flying the vehicle.

8.5 ISSUE 5: OPERATOR SELECTION AND TRAINING

UMVs are new technologies for most militaries around the world, and potentially require new jobs, positions, occupations, and units to command and control these assets. On the other hand, militaries have similar manned vehicles with similar payloads. The personnel that operate these vehicles are highly skilled and knowledgeable, and these skills and knowledge are potentially transferable to operating UMVs. Moreover, if UMVs were highly “intelligent” or “autonomous” then perhaps only general skill and knowledge levels would be required to operate the vehicles and their payload.

8.5.1 Conclusion 1

The best way to prevent the loss of operators’ skills is to periodically give the operators dedicated training. Another possibility is to require the operators to perform skill critical tasks manually at certain times, even though the task may have been allocated to the automated system.

8.5.2 Conclusion 2

Experience improves operators’ cognitive throughput, allowing them to devote limited attentional resources to future problems while automatically attending to immediate perceptual and motor tasks.

8.5.3 Conclusion 3

Teams comprising fundamental knowledge, skills, and abilities (KSAs) are better equipped to fulfil mission goals. KSA requirements are not completely transferable from in-person teams to virtual (distributed) teams and vice versa. The densely computer-mediated communication environment of the virtual realm requires a heightened adeptness at managing digital conflict, text-intensive interactions, and media selection.

8.5.4 Conclusion 4

Relative to virtual teams, social control is particularly valuable when the need for sharing tacit knowledge increases over socially impoverished channels of virtual communication, where conflict may escalate due to teamwork issues engendered by cultural difference in communication and problem-solving styles and approaches.

8.5.5 Conclusion 5

Teams need environments which facilitate efficient and effective command and control information sharing. When team members trust each other and the team infrastructure, are educated about organizational structure and processes, and understand information processing, fluid communication is enabled.

8.5.6 Conclusion 6

Team members need to quickly identify individual and team information needs, fulfil the needs, and disseminate, synthesize, and integrate that knowledge into mission activities. Consequently, situational awareness requirements can be addressed by supporting social networks with access to databases, human capital, and technology.

8.5.7 Conclusion 7

The transfer of skills and knowledge, and the requirement for general skill and knowledge levels will contribute to Force Multiplication by drawing from an existing, broader pool of people that can operate UMVs.

8.6 SUMMARY

A review of the many issues identified throughout this report highlights two major emphasis areas for future NATO RTO focus. The first area involves the study of tools and techniques for distributive collaboration/command and control of UMV teams. Issues of virtual teaming, communication bandwidth, collaboration methods and responsibility/authority are a few aspects of this important area. The second area centers on the methodologies and technologies to enable flexible human supervisory control of multiple, highly-automated UMV assets. Issues with this key area include human-automation challenges and mitigation techniques, flexible levels of automation, situation assessment and decision support tools for human-robot systems, multi-modal interfaces, and anticipatory support aids.

CONCLUSIONS AND SUMMARY



REPORT DOCUMENTATION PAGE																											
1. Recipient's Reference	2. Originator's References RTO-TR-HFM-078 AC/323(HFM-078)TP/69	3. Further Reference ISBN 978-92-837-0060-9	4. Security Classification of Document UNCLASSIFIED/ UNLIMITED																								
5. Originator Research and Technology Organisation North Atlantic Treaty Organisation BP 25, F-92201 Neuilly-sur-Seine Cedex, France																											
6. Title Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force																											
7. Presented at/Sponsored by Final Report of the RTO Human Factors and Medicine Panel (HFM) Task Group HFM-078/TG-017.																											
8. Author(s)/Editor(s) Multiple			9. Date July 2007																								
10. Author's/Editor's Address Multiple			11. Pages 514																								
12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.																											
13. Keywords/Descriptors <table border="0"> <tbody> <tr> <td>Adaptive interfaces</td> <td>Integrated systems</td> <td>Shared situation awareness</td> </tr> <tr> <td>Adaptive systems</td> <td>Intelligent support</td> <td>Situational awareness</td> </tr> <tr> <td>Autonomous operation</td> <td>Intelligent systems</td> <td>Supervisory control</td> </tr> <tr> <td>Cognitive cooperation</td> <td>Interoperability</td> <td>Systems engineering</td> </tr> <tr> <td>Control equipment</td> <td>Multi-modal interfaces</td> <td>UMV (Uninhabited Military Vehicle)</td> </tr> <tr> <td>Distributive collaboration</td> <td>Operational effectiveness</td> <td>Unmanned vehicles</td> </tr> <tr> <td>Flexible levels of automation</td> <td>Optimum operator/vehicle ratio</td> <td>Virtual team performance</td> </tr> <tr> <td>Human factors engineering</td> <td></td> <td></td> </tr> </tbody> </table>				Adaptive interfaces	Integrated systems	Shared situation awareness	Adaptive systems	Intelligent support	Situational awareness	Autonomous operation	Intelligent systems	Supervisory control	Cognitive cooperation	Interoperability	Systems engineering	Control equipment	Multi-modal interfaces	UMV (Uninhabited Military Vehicle)	Distributive collaboration	Operational effectiveness	Unmanned vehicles	Flexible levels of automation	Optimum operator/vehicle ratio	Virtual team performance	Human factors engineering		
Adaptive interfaces	Integrated systems	Shared situation awareness																									
Adaptive systems	Intelligent support	Situational awareness																									
Autonomous operation	Intelligent systems	Supervisory control																									
Cognitive cooperation	Interoperability	Systems engineering																									
Control equipment	Multi-modal interfaces	UMV (Uninhabited Military Vehicle)																									
Distributive collaboration	Operational effectiveness	Unmanned vehicles																									
Flexible levels of automation	Optimum operator/vehicle ratio	Virtual team performance																									
Human factors engineering																											
14. Abstract <p>Uninhabited Military Vehicles (UMVs) are used to augment manned forces in dull, dirty, or dangerous tasks. Human factors issues range from control station design, to vehicle interoperability, and integration with manned systems. New principles are reviewed for supporting the operator, and for collaboration between multiple operators. Future study is needed on techniques for distributive collaboration, command and control of UMV teams, and enabling flexible human supervisory control of multiple, highly-automated UMV assets.</p>																											





BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

DIFFUSION DES PUBLICATIONS RTO NON CLASSIFIEES

Les publications de l'AGARD et de la RTO peuvent parfois être obtenues auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la RTO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus soit à titre personnel, soit au nom de votre organisation, sur la liste d'envoi.

Les publications de la RTO et de l'AGARD sont également en vente auprès des agences de vente indiquées ci-dessous.

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivi du numéro de série. Des informations analogues, telles que le titre et la date de publication sont souhaitables.

Si vous souhaitez recevoir une notification électronique de la disponibilité des rapports de la RTO au fur et à mesure de leur publication, vous pouvez consulter notre site Web (www.rto.nato.int) et vous abonner à ce service.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE

Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr
(FIZBw)
Gorch-Fock-Straße 7, D-53229 Bonn

GRECE (Correspondant)

Defence Industry & Research General
Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

POLOGNE

Centralny Ośrodek Naukowej
Informacji Wojskowej
Al. Jerozolimskie 97
00-909 Warszawa

BELGIQUE

Royal High Institute for Defence – KHID/IRSD/RHID
Management of Scientific & Technological Research
for Defence, National RTO Coordinator
Royal Military Academy – Campus Renaissance
Renaissancelaan 30
1000 Bruxelles

HONGRIE

Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
P O Box 26
H-1525 Budapest

PORTUGAL

Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

CANADA

DSIGRD2 – Bibliothécaire des ressources du savoir
R et D pour la défense Canada
Ministère de la Défense nationale
305, rue Rideau, 9^e étage
Ottawa, Ontario K1A 0K2

ISLANDE

Director of Aviation
c/o Flugrad
Reykjavik

REPUBLIQUE TCHEQUE

LOM PRAHA s. p.
o. z. VTÚLaPVO
Mladoboleslavská 944
PO Box 18
197 21 Praha 9

DANEMARK

Danish Acquisition and Logistics Organization
(DALO)
Lautrupbjerg 1-5
2750 Ballerup

ITALIE

General Secretariat of Defence and
National Armaments Directorate
5th Department – Technological
Research
Via XX Settembre 123
00187 Roma

ROUMANIE

Romanian National Distribution
Centre
Armaments Department
9-11, Drumul Taberei Street
Sector 6
061353, Bucharest

ESPAGNE

SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

LUXEMBOURG

Voir Belgique

NORVEGE

Norwegian Defence Research
Establishment
Attn: Biblioteket
P.O. Box 25
NO-2007 Kjeller

ROYAUME-UNI

Dstl Knowledge Services
Information Centre
Building 247
Dstl Porton Down
Salisbury
Wiltshire SP4 0JQ

ETATS-UNIS

NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320

PAYS-BAS

Royal Netherlands Military
Academy Library
P.O. Box 90.002
4800 PA Breda

TURQUIE

Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi
Başkanlığı
06650 Bakanlıklar
Ankara

AGENCES DE VENTE

NASA Center for AeroSpace Information (CASI)

7115 Standard Drive
Hanover, MD 21076-1320
ETATS-UNIS

The British Library Document Supply Centre

Boston Spa, Wetherby
West Yorkshire LS23 7BQ
ROYAUME-UNI

Canada Institute for Scientific and Technical Information (CISTI)

National Research Council Acquisitions
Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications RTO et AGARD figurent dans les journaux suivants :

Scientific and Technical Aerospace Reports (STAR)

STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant :

<http://www.sti.nasa.gov/Pubs/star/Star.html>

STAR est édité par CASI dans le cadre du programme NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
ETATS-UNIS

Government Reports Announcements & Index (GRA&I)

publié par le National Technical Information Service
Springfield

Virginia 2216

ETATS-UNIS

(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)



BP 25

F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int



DISTRIBUTION OF UNCLASSIFIED RTO PUBLICATIONS

AGARD & RTO publications are sometimes available from the National Distribution Centres listed below. If you wish to receive all RTO reports, or just those relating to one or more specific RTO Panels, they may be willing to include you (or your Organisation) in their distribution.

RTO and AGARD reports may also be purchased from the Sales Agencies listed below.

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number. Collateral information such as title and publication date is desirable.

If you wish to receive electronic notification of RTO reports as they are published, please visit our website (www.rto.nato.int) from where you can register for this service.

NATIONAL DISTRIBUTION CENTRES

BELGIUM

Royal High Institute for Defence – KHID/IRSD/RHID
Management of Scientific & Technological Research
for Defence, National RTO Coordinator
Royal Military Academy – Campus Renaissance
Renaissancelaan 30
1000 Brussels

CANADA

DRDKIM2
Knowledge Resources Librarian
Defence R&D Canada
Department of National Defence
305 Rideau Street, 9th Floor
Ottawa, Ontario K1A 0K2

CZECH REPUBLIC

LOM PRAHA s. p.
o. z. VTÚLaPVO
Mladoboleslavská 944
PO Box 18
197 21 Praha 9

DENMARK

Danish Acquisition and Logistics Organization
(DALO)
Lautrupbjerg 1-5
2750 Ballerup

FRANCE

O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72
92322 Châtillon Cedex

GERMANY

Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr
(FIZBw)
Gorch-Fock-Straße 7
D-53229 Bonn

GREECE (Point of Contact)

Defence Industry & Research
General Directorate
Research Directorate
Fakinos Base Camp
S.T.G. 1020
Holargos, Athens

HUNGARY

Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
P O Box 26
H-1525 Budapest

ICELAND

Director of Aviation
c/o Flugrad, Reykjavik

ITALY

General Secretariat of Defence and
National Armaments Directorate
5th Department – Technological
Research
Via XX Settembre 123
00187 Roma

LUXEMBOURG

See Belgium

NETHERLANDS

Royal Netherlands Military
Academy Library
P.O. Box 90.002
4800 PA Breda

NORWAY

Norwegian Defence Research
Establishment, Attn: Biblioteket
P.O. Box 25
NO-2007 Kjeller

POLAND

Centralny Ośrodek Naukowy
Informacji Wojskowej
Al. Jerozolimskie 97
00-909 Warszawa

PORTUGAL

Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

ROMANIA

Romanian National Distribution
Centre
Armaments Department
9-11, Drumul Taberei Street
Sector 6, 061353, Bucharest

SPAIN

SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

TURKEY

Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi
Başkanlığı
06650 Bakanlıklar – Ankara

UNITED KINGDOM

Dstl Knowledge Services
Information Centre
Building 247, Dstl Porton Down
Salisbury, Wiltshire SP4 0JQ

UNITED STATES

NASA Center for AeroSpace
Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320

SALES AGENCIES

NASA Center for AeroSpace Information (CASI)

7115 Standard Drive
Hanover, MD 21076-1320
UNITED STATES

The British Library Document Supply Centre

Boston Spa, Wetherby
West Yorkshire LS23 7BQ
UNITED KINGDOM

Canada Institute for Scientific and Technical Information (CISTI)

National Research Council Acquisitions
Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of RTO and AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)

STAR is available on-line at the following uniform resource locator:

<http://www.sti.nasa.gov/Pubs/star/Star.html>

STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
UNITED STATES

Government Reports Announcements & Index (GRA&I)

published by the National Technical Information Service
Springfield

Virginia 2216

UNITED STATES

(also available online in the NTIS Bibliographic Database or on CD-ROM)